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HIGH ENERGY X-RAY STUDY

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Detector	X-ray beam energy	Target-object-distance
Source	X-ray beam intensity	Source-film-distance
Positioning System	Geometric unsharpness	Shielding
TELS	Total unsharpness	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study program investigated the feasibility, and developed a conceptual design, for an analytical/diagnostic X-ray system. This system would be used in existing AEDC test cells and would provide a capability to internally examine turbine engines and solid propellant rocket motors while operating under simulated altitude conditions.

Diagnostic X-ray capabilities in each test cell — J-1/J-2, C-1/C-2, and J-5 — were studied, and recommendations made. The participating contractors each developed conceptual plans for recommended equipment including the X-ray source, film detector, and positioning components.

In addition, test cell environment, portability/survivability, cell modifications, personnel safety/radiation shielding and equipment standardization were studied and recommendations were made.

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HIGH ENERGY X-RAY STUDY

SUMMARY

The objective of this study program was to determine the feasibility of incorporating diagnostic x-radiographic systems in several selected Arnold Engineering Development Center (AEDC) altitude test cells. The scope of work involved jet engine as well as solid propellant rocket motor testing, and was specifically directed to five test locations (Figure 1):

Test Cell	*Size — (Inside Diameter, ft)*	*Type of Engine*
J-1	16	Turbine
J-2	20	Turbine
C-1/C-2*	28	Turbine
J-5	16	Rocket

*Now under construction for the ASTF Program

After the preliminary analysis determined that a cell was reasonably capable of handling X-ray equipment, it was then a requirement for the contract participants to develop a conceptual plan for each location showing the equipment recommended: X-ray source, film detector, and positioning components. An estimate of the cost of each installation's conceptual design was required as part of the overall contract and is included as a separate document.

In conjunction with the above major objectives of this contract — installation feasibility, conceptual design, cost — several other points relating to safety and the operational aspects of the radiographic inspection systems were also considered. Basically they included:

- Effects of altitude test cell environment on quality and accuracy of radiographic measurement
- Portability and survivability of equipment
- Test cell modifications (where required)
- Personnel safety and radiation shielding
- Standardization of equipment, for both altitude cells and other test programs.

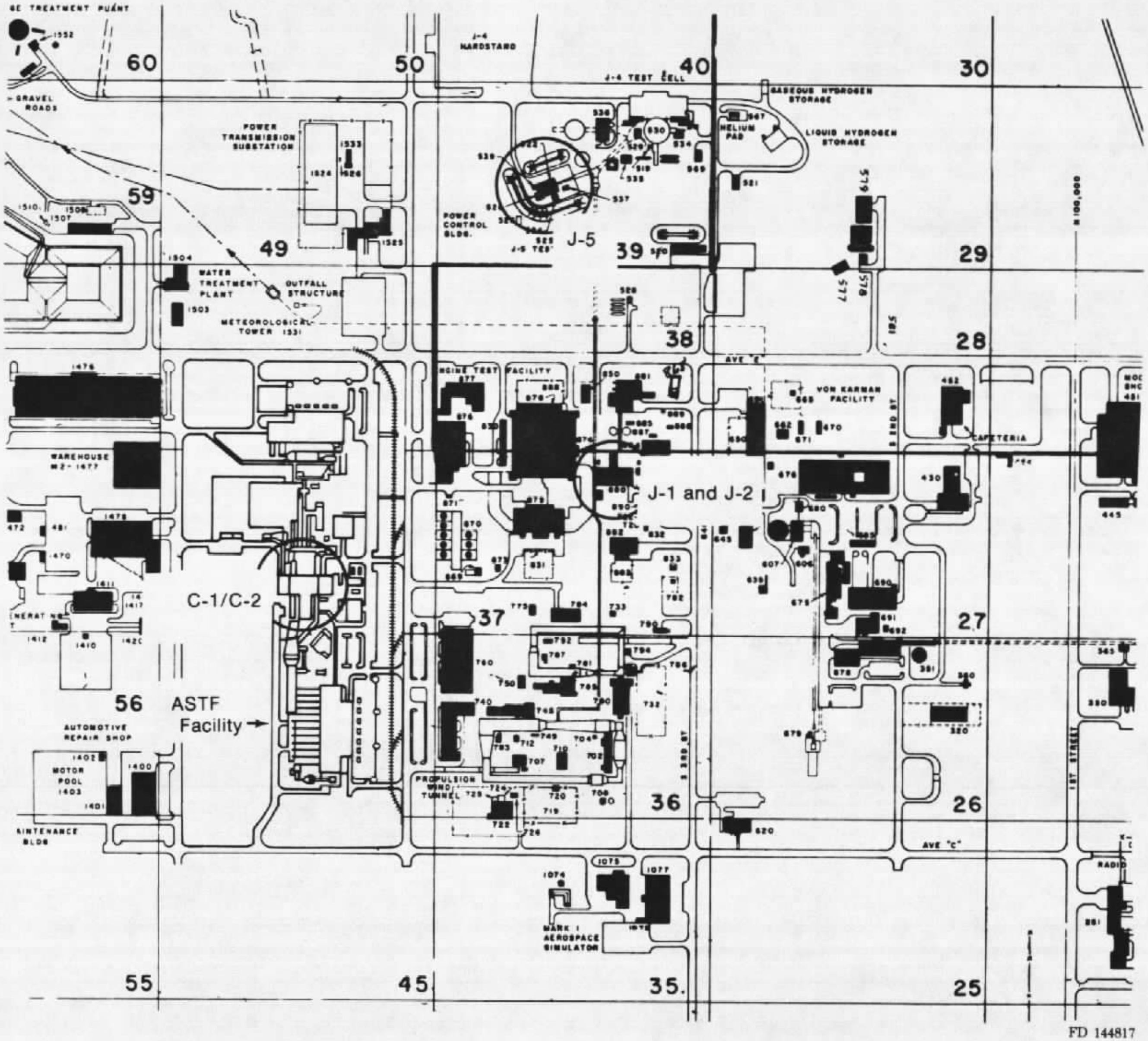


Figure 1. Plan for High Energy Study Test Cells

The information developed by this analytical study is expected to provide AEDC with the technical data necessary for selecting X-ray equipment for specific test locations in terms of maximum capability at minimum cost.

The performance of this study was accomplished as a joint undertaking by Pratt & Whitney Aircraft Group Government Products Division (P&WA/Florida), Lockheed Missiles and Space Corporation (LMSC), and Varian Associates, Incorporated. P&WA/Connecticut provided consulting services to the three participating companies through Mr. B. E. Kinchen.

The technical sections of this report describe the major areas of work by the three participants and were prepared specifically as follows:

Section 2 — X-ray Source Selection — A. H. McEuen, Varian, Inc.
Section 3 — Radiographic Protection — E. Tochilin, Varian, Inc.
Section 4 — Detector Imaging System — E. C. Yates, LMSC
Section 5 — Positioning System — M. K. Lewis, P&WA/Florida
Section 6 — Altitude Cell Image Quality — B. E. Kinchen, P&WA/Conn.

As noted in Appendix D, the study program was divided into three phases:

- Phase 1 — Criteria Definition and Field Survey of Test Cells
- Phase 2 — Preliminary Design and Final Conceptual Plans
- Phase 3 — Preparation of Final Report and Cost Estimate

It should be noted that early in Phase 2, with the concurrence of AEDC's technical representative, Captain Bibb Swain, the study participants concluded that J-1 was not a viable test cell for a radiographic system. The detailed reasons for this decision are covered in Section 5 (paragraph 5.2). As a result, Sections 2, 3, and 4 make little or no reference to this cell.

SECTION 1
INTRODUCTION/BACKGROUND

1.0 GENERAL

Continued development of more efficient gas turbine and rocket engines requires a detailed knowledge of the internal components and structures during operation. Current technological advances in turbine engine development have provided the capability for designing and building lightweight, more powerful propulsion systems. With a characteristic increase in thrust-to-weight ratios, engine structures tend to be more flexible and, therefore, more vulnerable to changes in internal clearances which can adversely affect performance and life-cycle costs. Utilization of X-radiographic techniques provides an accurate noncontact method of obtaining two-dimensional measurements of these changes in internal clearances.

The successful operation of a solid propellant rocket engine depends upon the integrity of the solid propellant-to-case bond, the degree of voids in the propellant, the propagation of the fuel/flame interface, etc. Again, X-radiography provides a unique method of obtaining detailed information about these parameters.

Clearance measurements of gas turbine and rocket engines have to date only been performed under sea level operating conditions. It is well known in turbine engine design that the temperature profile within the engine is vastly different at high altitudes than at sea level conditions. The rapid changes in inlet temperatures during mission profiles, from low speed, cold inlets to very hot inlets at Mach 3 or above, change the cooling flow balance and the internal temperature profile. This in turn, produces specific internal geometries that control the performance of the engine. Related effects could be evidenced in rocket engine performance.

The radiographic system that Arnold Engineering Development Center (AEDC) is proposing for their altitude test cells is a logical step toward increasing the understanding of these changes in internal clearances and how they vary at altitude conditions.

1.1 Scope

X-ray pictures of internal parts of an operating jet or rocket engine showing sufficient resolution to define the parameters of interest, require a high energy, high intensity *source* of X-radiation coupled with a high speed, high resolution *detector*. The source and the detector must be *positioned* accurately with respect to the object to be X-rayed to allow proper "focusing"

of the radiographic components. This study, therefore, addresses four major areas of interest for such a system:

- Source
- Detector
- Positioning
- Safety.

1.2 Background

1.2.1 Turbine Engine Radiography

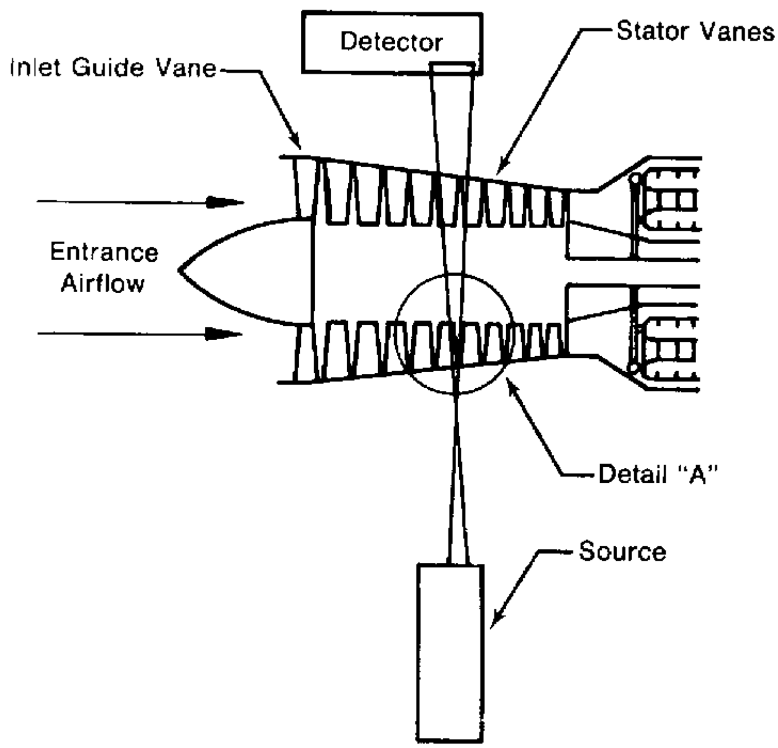
1.2.1.1 General Techniques

The objective of engine radiography is to determine the extent of the relative motion that occurs between the internal components of the engine over its complete operating regime. Of interest in gas turbine engines are axial shifts between the rotor and stator components and, more particularly, the changes in clearances between seal components, and between blade tips and blade tip seals. Even small errors in the relative positions of these components can cause significant performance losses, and rubbing during engine transients causes excessive wear and reduces engine life.

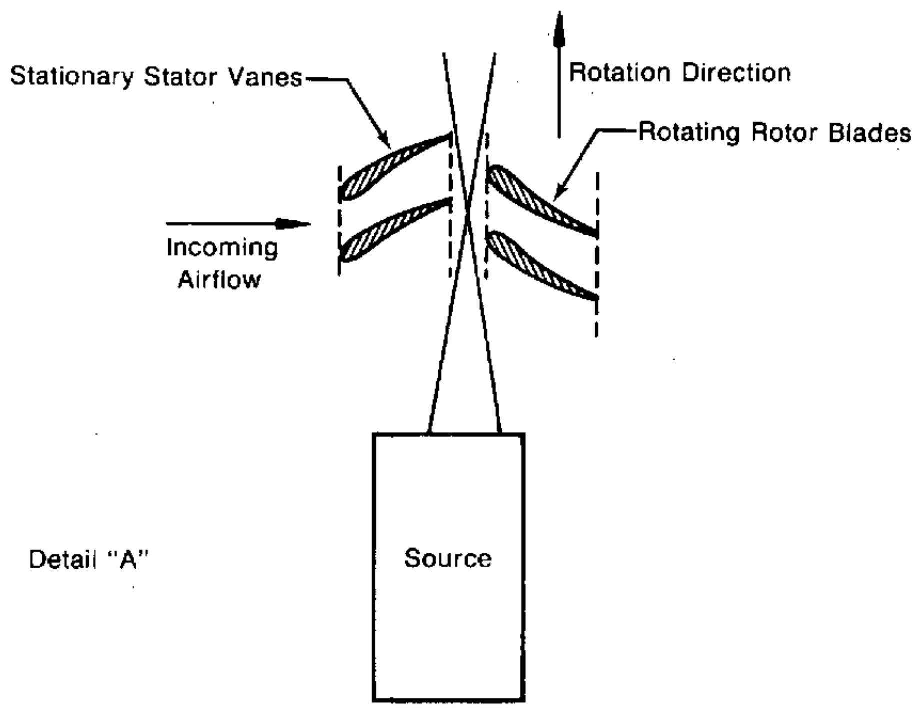
Figures 2 and 3 illustrate in simplified form, the configuration of the X-ray source-engine-detector path when making axial and radial clearance measurements. The principal rays forming the image of the object to be radiographed (stator hub and blade tip shroud, respectively) are shown. The task of the radiographer is to measure clearances from radiographs of this type. Included in the roster of measurements needed are:

- Axial and radial clearance of knife-edge seals
- Radial clearance of unshrouded blades
- Labryinth seal clearances
- Axial clearances between rotor and stator components
- Component deflections due to mechanical and thermal stress.

These measurements must be made at various locations within the engine. This dictates flexibility and precision in positioning the X-ray source and detector.



Plan View of Compressor Section



Radiographic Inspection Point Showing Axial Clearance Between Stator and Rotor Components

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Figure 2. Geometry of X-ray Source-Engine-Detector for Obtaining X-Radiographs of Axial Clearance Measurements

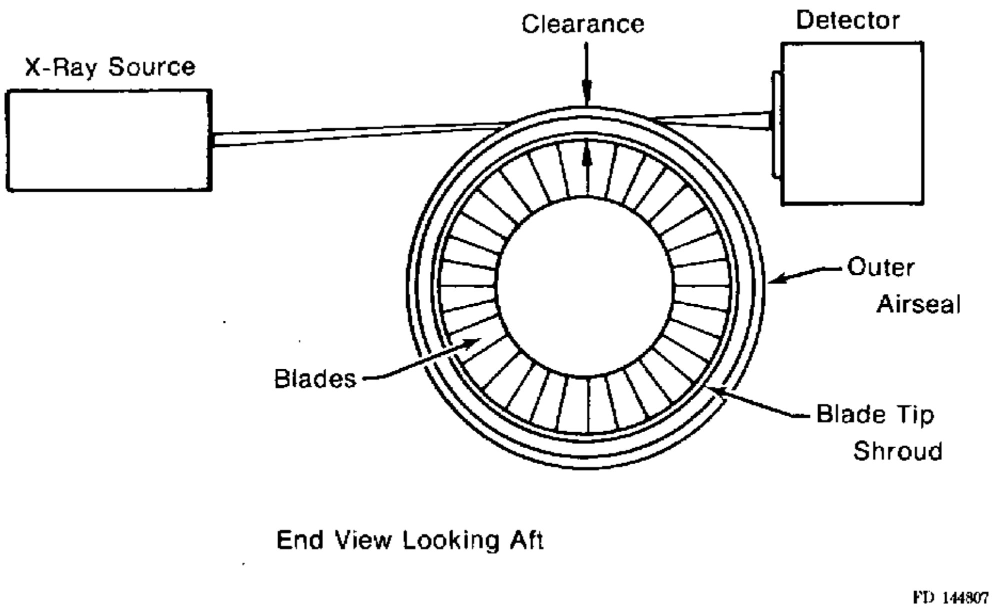


Figure 3. Geometry of X-ray Source-Engine-Detector for Obtaining X-Radiographs of Radial Engine Clearances

The internal structure of the engine can be complex and, consequently, the projected image of the gap being measured can sometimes have superimposed images of other extraneous components in the foreground and background. In addition, many of the edges to be located are not square but have an intrinsic blur factor due to their curvature; that is, there are inside or outside surfaces of cylindrical shells or similar structures.

As figure 3 shows, the path of the X-ray for radial clearance measurements is along chords through cylindrical shells, and the slant thicknesses, therefore, can be much larger than the shell thickness. Since it is desirable to test all classes of engines (with rotor diameters from <1 ft to 10 ft), metal slant thicknesses encountered will range from <1 in. to 16 in., and the desired accuracy of these measurements will vary considerably with each case. Sometimes gross motions and distortions are of greater interest and accuracy is not important; and sometimes accuracy greater than ±0.001 in. is needed. In general, for smaller engines, gas path seal measurements accurate to within ±0.003 in. are useful, but in much larger engines, an accuracy of ±0.010 in. is frequently sufficient.

Engine testing requires that radiographs be obtained under the following engine conditions:

- Static, with the engine shut down
- Steady-state running at constant thrust or power level
- Acceleration and deceleration transients.

For turbine engines, the requirement that radiographs be taken while the engine is running means that the rotor blades will be in motion, and that other motions such as inherent vibrations might be present. The X-ray equipment itself will be subjected to high noise levels, strong vibrational excitation, and significant aerodynamic loading caused by air circulation in the neighborhood of the engine.

Vibration usually is not a major concern in turbine engines since they are designed to specifications requiring vibration amplitudes to be less than a few thousandths of an inch. Therefore, for steady-state measurements, exposure times of several minutes can be made in most cases without any problems with drift in engine operating parameters or with blurring caused by engine vibration.

For transient measurements, however, such as snap accelerations and decelerations, significant changes in clearance can occur within a few seconds and, consequently, exposure times of less than 1 sec are required. Transient measurements are of particular importance in engine design. The action of the engine components during rapid acceleration and deceleration determines the minimum clearances that can be set between the rotating and static components. Most of the responses of interest in static testing are due to thermal rather than centrifugal and aerodynamic loads and are rather slow in comparison.

The limiting thickness sensitivity of high energy radiographic techniques presents another problem in radiographic engine testing. Most turbine engine rotors do not contain blades with shrouded tips, and if the blade tip thickness is below the minimum discernible thickness of the radiographic technique, the tip cannot be resolved. The apparent oscillation of the blade tip relative to the X-ray beam caused by the component rotation makes the problem even more complicated. Even when the blade tips can be resolved when the engine is stopped, they cannot always be resolved when the engine is in operation. The approach used to overcome these problems include data reduction techniques, special test techniques, and mechanical image enhancement. Clearance measurements involving blade tips that are imaged under static engine conditions can be obtained under engine operating conditions by data reduction techniques which are supplemented by a strobe test technique. This technique involves pulsing the X-ray source once per engine revolution. A facility for stepping the X-ray source pulse in 1-degree phase increments from the engine pulse allows measurements of individual blade tip clearances, or the investigation of a specific point of interest on a rotating structure. Finally, blade tips or components which are not discernible can be treated locally with a high attenuation coefficient material so that they can be imaged by the radiographic system.

1.2.2 General Design Considerations

The primary design considerations for an engine radiographic facility are the X-ray source characteristics, the geometric arrangement of the source-engine-detector, and the detector characteristics.

1.2.2.1 X-Ray Source

The X-ray source is characterized by: (1) the *energy* of the stimulating electron beam which relates to the wavelength spectral distribution of the resulting X-rays, (2) the *intensity* of the X-ray beam, and (3) the *size of the target* from which the X-rays are emitted.

Energy level and intensity are closely interrelated. For a given intensity, increasing the energy level increases the ability of the X-ray to penetrate the engine, permitting shorter exposure times. The increased energy levels also result in increased secondary emissions of X-rays within the detector system, resulting in some blurring of the image at high energy levels. Alternatively, for a given energy level, increasing the intensity reduces the exposure times, but also increases the amount of scattered radiation. This reduces the contrast of the image if it reaches the detector. The choice, then, becomes one of selecting an energy level that provides adequate penetration of the engine and an intensity that results in reasonable exposure times to provide good images on the detector. The typical choice is a source with an energy in the 8-MeV range with an intensity on the order of approximately 2000 rads/min.

Ideally, a large source emitting a collimated parallel beam of X-rays is desired. Such a source would project a sharp, undistorted and unmagnified image. However, since such a source is not currently achievable, the ideal alternative would be as small as possible, i.e., a point source which provides a sharp, although geometrically distorted image. Since X-ray sources cannot be true point sources, the X-ray images have a penumbra shadow at their edges which appear as a blur. For the industrial purposes required under this contract, it has been established that the minimum practical size of the source target is approximately 1 mm in diameter. Other basic requirements for the sources are shown in paragraph 1.4.1.

The selection of a suitable X-ray source for the turbine engine altitude testing program envisioned under this study evolved into an evaluation of three categories of equipment:

- Standard off-the-shelf equipment
- Standard equipment, modified
- TELS concept high energy equipment.

It was concluded earlier in the program that the selection of an existing standard X-ray machine that could be used directly or reasonably adapted through redesign to meet this application, would benefit the program regarding cost and operational reliability.

The inclusion of the TELS source concept, however, stemmed from the recognition that existing X-ray equipment for industrial purposes might be too large for use inside an altitude chamber. The "miniaturization" of a high energy source, as proposed by Varian Associates, Inc., in their portion of the "TELS Radiographic System Study,"[1] would accomplish sizeable reductions in weight and volume over similar equipment now being used by manufacturers. Basically the design embodies a new linear accelerator guide assembly which offers two improvements of significant importance to the AEDC altitude test application:

- Increased production of energy per unit length of accelerator (allowing a reduction in depth of the equipment)

- Reduction in peak RF fields (intensity) for a given energy level (decreasing undesirable radiation scatter).

By using this new accelerator guide coupled with a shift in the operating RF frequency from "S" band (used in present accelerators) to the higher "C" band frequency, Varian indicates that not only will the development of a smaller more powerful accelerator be possible, but also a corresponding reduction in size and weight of the other microwave components in the source package can be accomplished. The inherent ruggedness of the TELS source design required by the high "g" load test environment also offers a further advantage in its use within the altitude chambers.

1.2.2.2 Geometric Arrangement

The geometric arrangement of the source-engine-detector is extremely important, both in terms of the distortion of the image and its suitability for analysis to determine clearances accurately. This is illustrated in simplified form in Figures 2 and 3.

The X-ray source located on one side of the engine provides a supply of high energy X-ray photons capable of penetrating the metal thickness of the engine. The engine components modulate the electromagnetic radiation by various attenuation mechanisms with the primary mechanism, in the energy range of interest, being Compton scattering. The radiation exits the engine and is detected by the detector system.

Alignment of the X-ray source and detector play an important role in the formation of the resultant radiograph and the capability to make an accurate dimensional measurement. The relationship between the X-ray source diameter (D), the distance between the X-ray source and the engine (TOD), and the engine-to-detector distance (OFD) directly determine the radiographic magnification and affect the spatial resolution.

The radiograph magnification (M) is given by:

$$M = \frac{TOD + OFD}{TOD} = \frac{W_x}{d} \tag{1}$$

where,

W_x = the clearance width in the plane of the detector

d = the true clearance width.

Because a point source of X-radiation cannot be realized, a penumbra is formed. The penumbra produces geometric unsharpness (μ_g) which is represented by:

$$\mu_g = \frac{OFD}{TOD} D = (M-1)D \tag{2}$$

This geometric unsharpness is one of the components contributing to edge blur on a radiograph. The total radiographic unsharpness, however, is composed of several components. In addition to the geometric unsharpness, blur is caused by detector unsharpness (μ_r) and screen unsharpness (μ_s). These components combine approximately in the following manner to provide a total unsharpness μ_t:

$$\mu_t = (\mu_g^3 + \mu_r^3 + \mu_s^3)^{1/3} \tag{3}$$

This total radiographic unsharpness is inherent in the geometry and equipment used and generally determines the limiting resolution of a specific radiographic technique. Additional blur can occur, however, from lack of contact between the intensifying screens and the film and by vibration. These causes can often be eliminated through increased care in obtaining the radiograph.

Radiographic magnification is desirable in the measurement of small clearances. It aids in measuring the small clearance dimensions, and it permits the X-ray source to be positioned closer to the engine, thereby reducing the spatial envelope required by the radiographic equipment.

However, increasing the magnification also increases the geometric unsharpness. The optimum compromise between magnification and unsharpness can be determined from combining the effects of Equations 2 and 3. If the unsharpness produced from the detector and the screen are combined in a single parameter, μ_{fs}, and Equation 3 is then plotted relative to the level of μ_{fs} as shown in figure 4, changes in geometric unsharpness have negligible effect on the total unsharpness until the geometric unsharpness exceeds the level of the combined detector and screen unsharpness. The positions on this curve of the AEDC altitude test cells are indicated. These points were calculated assuming the X-ray source was *contained within* the altitude test cell. Since the film/screen unsharpness will be in the range of 0.5 mm, this illustrates a significant problem with the J-1 and J-5 test cells if the source must be mounted inside the chamber.

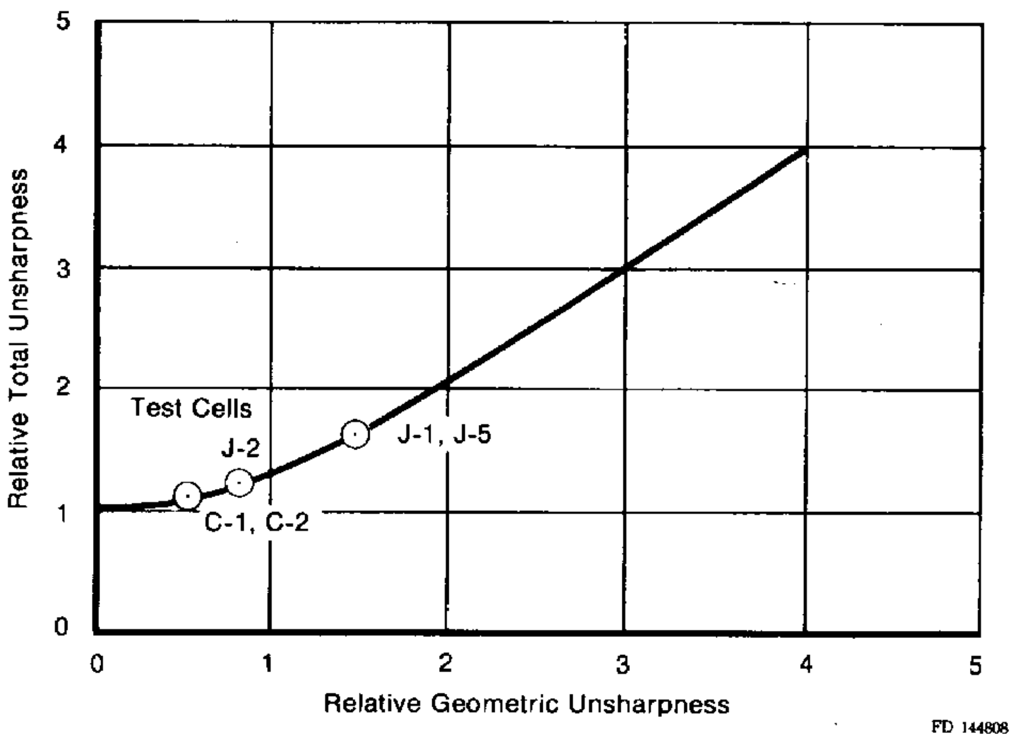


Figure 4. Effect of Geometric Unsharpness on Total Unsharpness

Generally, the spatial resolution of a system is established by evaluating it in terms of its spatial frequency response. The frequency response function is called the "modulation transfer function" (MTF). The MTF is the ratio of the Fourier transform of the output and the Fourier transform of the input. As such, it provides a convenient description in frequency space of how a system alters the input. These Fourier transforms and thus the MTF exist if the input and

output are smooth and absolutely integrable as is the case in X-radiography. The spatial frequency response of every component of a system can be evaluated individually and the total system modulation transfer function obtained by multiplying the individual MTFs together or the total system MTF can be evaluated as a single entity.

The MTF of a circular source of uniform emission is given by the following expression:

$$\mathrm{MTF} = \frac{J_1\,(2\alpha\pi a f)}{\alpha\pi a f} \tag{4}$$

where,

a = radius of source

f = spatial frequency

$\alpha = \dfrac{\text{Object to film distance}}{\text{Source to object distance}} = M\text{-}1$

M = Magnification

J_1 = Bessel function of first order

This equation was utilized to estimate the resolution to be expected in the various AEDC test cells. The results are shown in Figure 5.

Another consideration is that radiographing narrow, deep channels causes collimation of the X-ray beam. If the geometric unsharpness is significant, a decrease in total unsharpness will occur. In addition, the magnification will be reduced. If this reduction of magnification is not recognized, errors will result when the measurements are corrected for magnification.

An engine radiography exhibits "ellipsing" if the cylindrical section is not aligned along the central ray of the beam. This phenomenon can be used to advantage to determine the axial motions of the internal components relative to the center of the X-ray beam. By measuring the changes in the ellipsing and the radial position at which the ellipsing is measured, the change in axial position relative to the center of the X-ray beam can be calculated.

Generally, *the source should be as far from the engine as possible while the detector should be as close as possible.* Moving the source far from the engine allows it to more closely approximate a point source, reducing the penumbra region at the edges of the images and also reducing the distortions of the image. However, *physical limitations such as found in the AEDC altitude test cells as well as X-ray source intensity limitations restrict the distance that can be achieved between the source and the engine.*

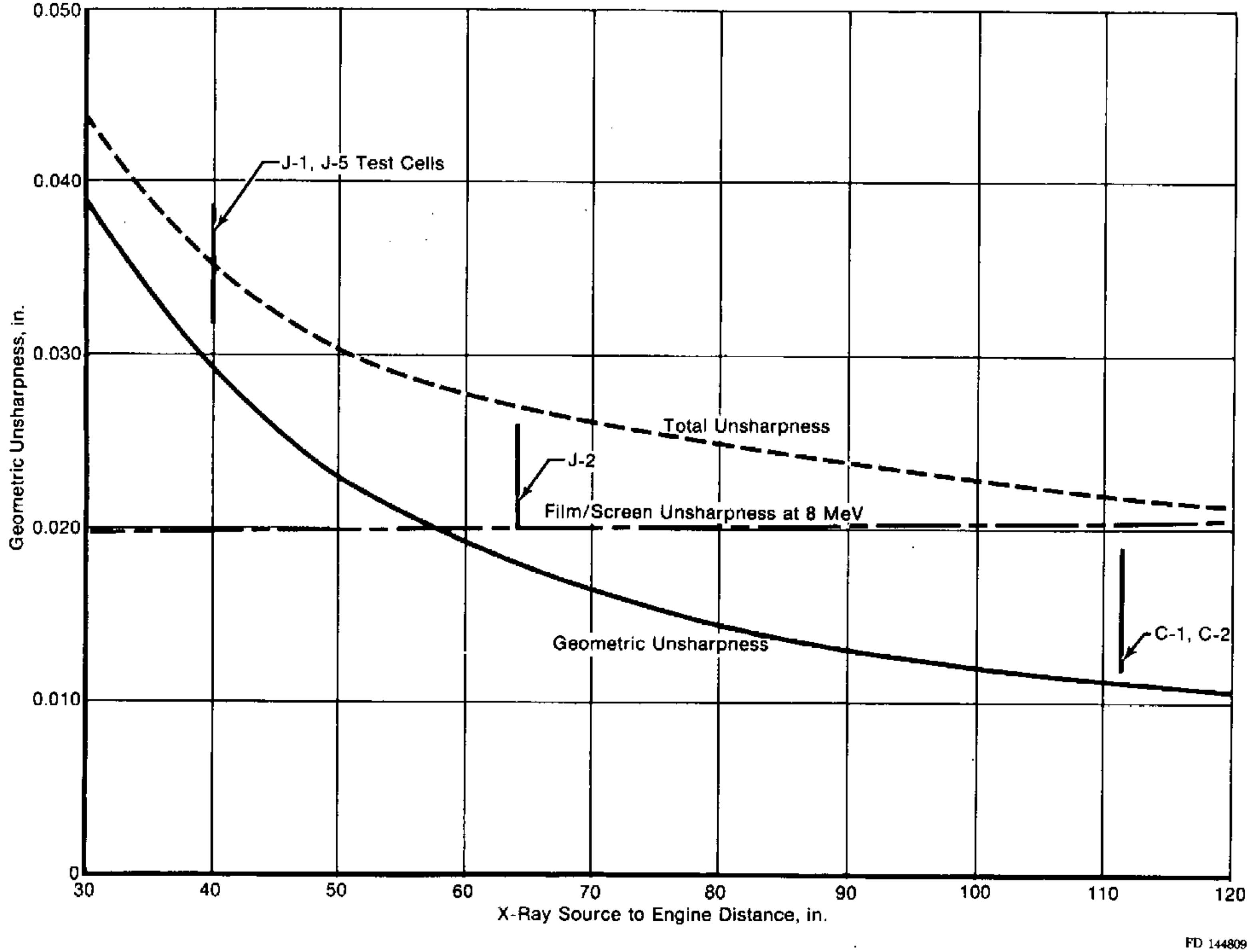


Figure 5. Modulation Transfer Function for Uniformly Emitting Circular Source

Great care must be taken to stabilize the X-ray source. If adequate care is not taken to ensure that there is no vibration of the source relative to the engine, the vibration will result, in effect, in a larger source size. The resulting radiographic image will show an increase in unsharpness similiar to that of excessive engine vibration.

Keeping in mind the importance of the X-ray position with respect to the object being radiographed and the inherent restrictions (figure 6) presented to such positioning at or within the altitude test cells, it was determined that all candidate machine performances would be calculated and evaluated for three conditions for each test chamber, namely:

- X-ray source mounted *inside* the chamber located at the maximum TOD distances possible in order to minimize the geometric unsharpness.
- X-ray source mounted *outside* of the chamber "firing" through the cell wall. This configuration assumes a modification to the cell by substituting a low transmission-loss material such as aluminum for steel where the beam penetrates the chamber.
- X-ray source mounted inside the test cell, but with an external *bubble* on the cell wall permitting the source to be positioned at the optimum distance for minimum image unsharpness.

The detailed evaluation of these options is more fully covered in Section 2.

1.2.2.3 Detector

Detector unsharpness is a characteristic of the detector used and the energy of the X-ray employed. If film is employed as the detector, the unsharpness has been found to vary as shown in figure 7[2]

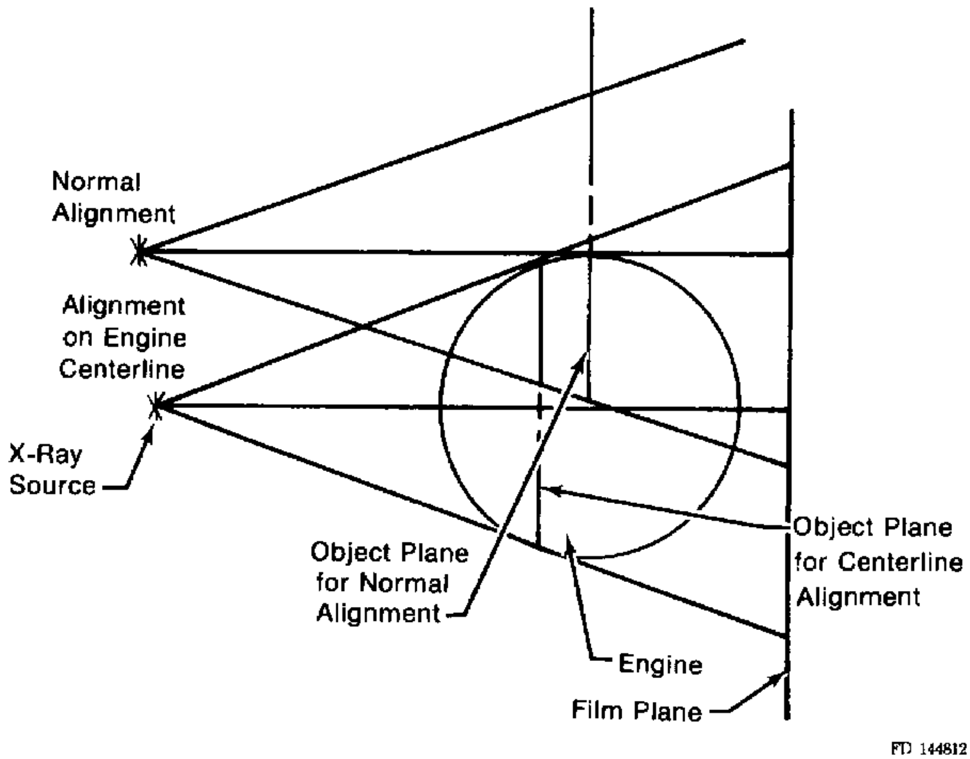


Figure 6. Effect of X-ray Source Alignment on Distortion Shows Source-Engine Alignment Affects Image Distortion and Engine Plane Image

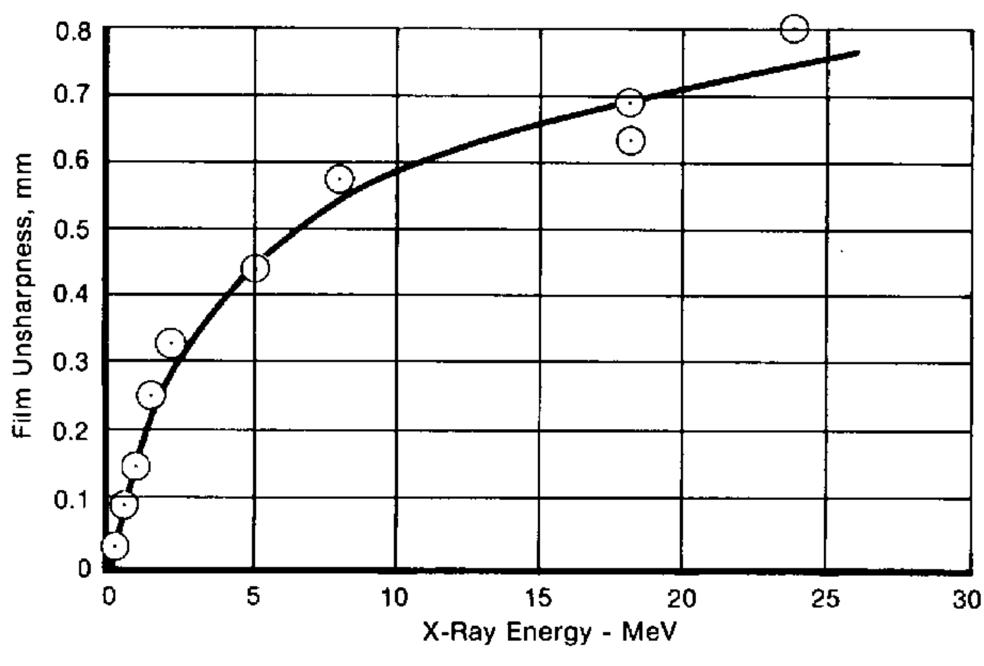


Figure 7. Experimental Values of Film Unsharpness for a Fine-Grained X-ray Film as a Function of X-ray Energy Level

The X-ray energy absorption processes (Compton screening, pair production, and photoelectric effect) which produce a photographic image do so by the creation of secondary electrons which react with the silver halide grains in the emulsion. To augment the film sensitivity and obtain reasonably short exposure times, lead intensifying screens ranging in thickness from 0.1 to 1.0 mm are placed in contact with the object side of the film to increase secondary electron flux incident on the film for a given primary X-ray beam intensity. The high-energy X-rays used in engine radiation produce an energetic secondary electron in the screen and in the emulsion itself which can diffuse in appreciable distances, producing substantial image blur. Since this is an inherent property of the film-intensifying screen combinations used, it is referred to as film and screen unsharpness. The overall effect is that each original high-energy X-ray photon can produce more than one developable grain in the photographic emulsion, and these grains are distributed some distance around the point at which the path of the original X-ray photon intersects the film plane. For X-rays in the energy range required for engine radiography, the film unsharpness is about 0.5 mm.

An additional image degradation results from scatter X-radiation resulting from the attenuation process. The quantity of scatter incident on and recorded by the detector system is dependent upon the following factors:

- X-ray spectrum
- Total exposure
- Proximity of the scatter device to the detector
- Sensitivity of the detector to the scatter spectrum
- Thickness of the object being radiographed.

In the radiograph of a 20-mm thickness of steel, the scattered radiation is almost twice the level of the primary radiation reaching the detector. The scatter radiation tends to reduce the contrast of the image making the location of the edges of interest exceedingly difficult. Scatter radiation cannot be completely eliminated; however, the utilization of appropriate shielding about the detector reduces the scatter radiation to acceptable levels in most cases in engine radiography. This subject as it applies to the altitude test cells is further discussed in Section 6.

Establishment of a detection system conceptual design that met all of the requirements stated by AEDC was considered a very challenging effort. The preliminary study work during Phase 1 of the J-1, J-2, C-1/C-2 and J-5 test cells combined with an evaluation of the test objects, source requirements, and inspection requirements led to findings that the imaging system design approach should include sufficient flexibility to permit implementation under a wide variety of changing environmental, physical, and radiological conditions.

1.2.3 Solid Propellant Rocket Motor Radiography

1.2.3.1 General Techniques

Although radiography of solid propellant rocket motors is currently limited to nondestructive testing on the production line and for prefire inspection, the dynamic X-ray inspection capability as AEDC proposes will extend this technology toward providing data for improved propulsion system design and operational control. Radiographic inspection of solid propellant rocket motors in comparison with that for turbine engines, indicates however, a somewhat different capability. Past experience by Lockheed Missile and Space Company (LMSC) on the Trident Program which was conducted to detect typical solid rocket motor defects, e.g., case bond separation and propellant grain voids, showed that the optimum source energy and flux required were in the range of 12 MeV and 4000 rads/min at 1 min respectively (vs 8 MeV and 2000 rads for turbine engines). Therefore, it was recognized early in this study that the development of a system for J-5 to record burning phenomena and nozzle/throat profiles during rocket firing would, in all probability, require equipment and techniques not precisely matching those for the turbine engine cells. The objective of maintaining commonality of all items of equipment appeared at the outset to be a difficult task; however, the imaging system design emerged as the most promising component that could be tailored to match the source-object-detector criteria parameters for both tests.

1.2.4 Shielding Requirements

A major design requirement for an X-radiographic test facility is that suitable radiation shielding protection and operational procedures be provided to ensure that no individual receives radiation in excess of the maximum permissible dose. Both local and federal standards must be adhered to in order to satisfy AEDC requirements. Radiation protection standards are set forth in Table 1. The Tennessee State Regulations[8] are the most stringent relative to permissible dose, but basic calculations for shielding requirements are performed using the guidelines and data given by the National Council on Radiation Protection and Measurements in NCRP Report No. 34.[4]

Appropriate radiation protection can be obtained by a variety of techniques and combination of methods. Radiation can be attenuated by distance and through appropriate high density mediums including soil, concrete, steel, etc. Therefore, both local shielding and limited access to particular areas are often used to provide the required degree of radiation protection.

TABLE 1. RADIATION PROTECTION STANDARDS[3-6]

	REMS per Quarter
1. Whole body; head and trunk, active blood-forming organs, lens of eyes	1 ¼
2. Hands and forearms, feet and ankles	18 ¾
3. Skin of whole body	7 ½

1.2.5 Special Considerations for the AEDC Altitude Test Cells

1.2.5.1 General

In addition to the needs experienced in sea level test stands, other particular design requirements arise as a result of altitude testing. These are a result of:

- Increased scatter radiation due to the steel walls of the test cell and their close proximity to the detector system.
- Restriction on TOD due to the limited size of the test cells.
- Environmental considerations:
    - Extremes of temperature, humidity, and subatmospheric pressures. Condensation and precipitation will be especially troublesome to high voltage components and must be adequately guarded.
    - Vibrational frequencies over a wide spectrum which will be dependent upon the engine under test, its power setting, operating point, etc.
    - Extreme acoustical and mechanical vibration loads induced by the engine under test.
- Foreign object damage (FOD) caused by over-pressurization of the rocket engine cases or a turbine engine failure.
- Need for portability.

A discussion of these requirements follows.

1.2.5.2 Scatter Radiation

The proximity of the steel walls of the altitude test cell, the engine mount system, and the image system positioner produce an adverse environment for X-radiography. This condition is expected to produce a higher level of scatter radiation than encountered in sea level testing. It results in a lower accuracy of the resulting measurements unless adequate care is taken to design an imaging system that is relatively insensitive to the scatter radiation.

Several design approaches exist for minimizing the effect of scatter radiation. Since scatter radiation is of a lower energy than the primary image carrying radiation, the utilization of intensifying screens that have lower sensitivity to the scatter radiation and backscatter shields near the imaging system sharply decreases the effects of scatter radiation.

The reduction of the X-ray beam angle to a size sufficient to produce the desired radiographic image eliminates unnecessary interaction of the X-ray beam with potential scatterers and thereby reduces the scatter radiation incident on the imaging system.

1.2.5.3 Target-to-Object Distance (TOD)

The relatively small diameter of altitude test cells creates a significant problem in X-radiographic measurements. As previously mentioned, the geometric arrangement of the various components of the radiographic system directly affects the resulting resolution of the system. The estimated radiographic unsharpness is shown in figure 4 for the respective AEDC test cells, assuming the X-ray source is contained within the test cell, and that the full cell diameter can be utilized. Figure 8 illustrates the estimated modulation transfer functions for the various cells and for the P&WA/Florida sea level test facility. These MTF's do not include film/screen effects. From these preliminary results, the feasibility of obtaining 0.57% thickness sensitivity and 0.13-mm resolution in the J-1 and J-5 test cells appeared questionable.

An alternative approach in this study was to move the source outside of the test cell and irradiate the engine through the wall of the test cell. The disadvantages to this plan were manifested by an increase in the radiation flux requirements and consequently, the scatter radiation. This technique was optimized, however, by the installation of a low attenuation window into the wall of the test cell.

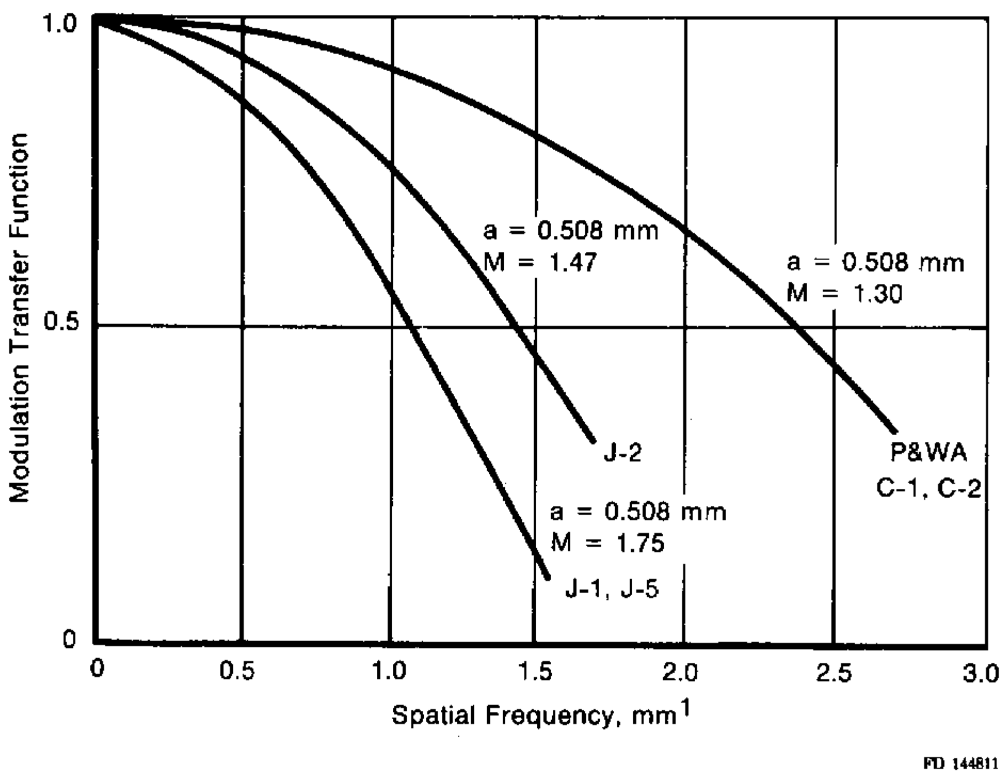


Figure 8. Estimated Radiographic Unsharpness for AEDC Test Cells

1.2.5.4 Environmental Considerations

The temperature extremes encountered during altitude testing present a potential problem in radiography. Excessive temperature will cause fogging and distortion of the X-ray film which, in turn, will cause a malfunction in the film transport mechanism. These items directly affect the accuracy of a radiographic clearance measurement. The film transport (imaging system) must provide provisions to maintain the system at a uniform temperature compatible with the reliable operation of the radiographic measurement.

The radiographic equipment will be exposed to acoustical and mechanical vibratory loading and other vibrational frequencies. This, coupled with extremes of temperature, humidity, and subatmospheric pressures produces a difficult environment for a radiographic system. The design concepts must employ adequate environmental housings to minimize the effects of the parameters on the radiographic system.

1.2.5.5 Foreign Object Damage (FOD) Survivability

In any testing operation, occasional failure of the test article is to be expected. All successful test cell designs incorporate features to harden the expensive interface equipment and

instrumentation systems to minimize costly damage to these systems and to limit test cell downtime after a test article failure. The film changer and real-time imaging system will necessarily be in the near vicinity of the object being inspected and will be subject to damage in the event of catastrophic failure, as will be the source when located inside the test cell.

While certain steps can be taken to protect portions of the radiographic system components, it is essential that the source, intensifying screens, portions of the film changer, and portions of the optical transfer system be in a direct line of sight with the test object. Although the intensifying screens are a rigid heavy metal, it is likely that direct impact from a solid object will result in damage. To the extent that such damage is unavoidable, it will be necessary to replace the components. This and other problems of equipment protection and survivability are considered in all components of the system.

1.2.5.6 Portability

The utilization of the costly radiographic system can be increased several times if the system can be made portable. The ideal installation at AEDC will consist of several altitude test cells, each of which has been modified to accept the radiographic systems, including a single source and detection system that is capable of being transported and erected at any test cell.

One goal of this study was to develop a conceptual design for a portable radiographic system. The detection system is relatively small and easy to transport and lends itself to commonality more readily than the X-ray source. The problem in portability was recognized early as being centered on the X-ray source. A preliminary survey of commercially available high-energy X-ray equipment suitable for the AEDC test requirements showed weights ranging from 1 to 4 tons. The original TELS source package at 1000 lb offered a very reasonable alternative.

1.3 Criteria Definition and Tasks

During the initial part of Phase 1 key work tasks were identified as being necessary to meet the basic criteria established by the AEDC contract Statement of Work. Each major task was further defined through identification of subtasks. The results of this task and subtask definition as outlined below established the objectives for the "High-Energy X-ray Study" participants.

1.4 Key Tasks (Responsible Participant)

- X-ray source requirements (Varian)
- X-ray imaging requirements (Lockheed)

- X-ray positioning requirements (P&WA/Florida)
- Personnel radiation shielding (Varian)
- Effects of altitude test cell on the quality of radiographic clearance measurements (P&WA/Conn.)
- System survivability (All)
- System portability (All)

1.4.1 X-ray Source Requirements (Varian)

- General Design Requirements

Turbine Engine

1.	Bremsstrahlung spectrum	- Must contain X-ray photons with energies to 8 MeV
2.	Bremsstrahlung flux	- A minimum of 50 rad/sec at 1m
3.	X-ray source shape	- Circular
4.	X-ray source diameter	- Less than or equal to 1.0 mm
5.	X-ray pulse width	- 2 to 5 μsec
6.	X-ray pulse rate	- Adjustable from 50 to 350 pulses per sec
7.	Total X-ray field angle	- Adjustable from 8 to 1 deg (10 deg $\times$ 6 deg)

Rocket Engine

1.	Bremsstrahlung spectrum	- Must contain X-ray photons with energies to 15 MeV

2. Bremsstrahlung flux - A minimum of 100 rad/sec at 1m

3. X-ray source shape - Circular

4. X-ray source diameter - Less than or equal to 1.0 mm

5. X-ray pulse width - 2 to 5 μsec

6. X-ray pulse rate - 60 to 180 pulses per sec

7. Total X-ray field angle - Adjustable from 20 deg to 1 deg (15 deg × 20 deg)

- Determine optimum source parameters for AEDC requirement — size, weight, energy, output, and controls.
- Establish technical feasibility of these parameters.
- Determine the viability of a single X-ray source versus multiple source concepts.
- Evaluate the effects of environment on the source and provide conceptual solutions to any problems:

  1. High temperature
  2. Condensation
  3. Low pressure.

1.4.2 X-ray Imaging System Requirements (LMSC)

- Similar to X-ray source as stated above.
- Conformance with AEDC requirements including:

  1. Film frame rate - 1 frame per sec

2.	Film spatial resolution	- Engine clearances of 0.005 through 3.5 in. of steel, rocket motor requirements TBD
3.	Film density sensitivity	- 0.020 in. in 3.5 in. of steel (0.57% of total thickness)
4.	Real-time capability	- Required for accurate system alignment.

1.4.3 X-ray System Positioning (P&WA/Florida)

- Determine design details

  1. Positioning requirements:

     - Degrees of freedom
     - Remote positioning
     - Positioning accuracy
     - Stiffness required
     - Size.

  2. Develop concept suitable to meet radiographic and space requirements.

  3. Structural requirements for good radiographs might conflict with flexibility requirements and vice versa.

1.4.4 Personnel Safety and Radiation Shielding (Varian)

- Calculate total exposure at various locations based upon expected workloads, occupancy factor, and utilization factors for existing facilities.

- Calculate additional shielding required to maintain exposure levels at recommended levels.

- Determine feasibility of adding additional shielding, restricting area, etc., to accomplish required exposure level.

- Determine control systems required to implement personnel protection.

1.4.5 *Effect of Altitude Test Cell on the Quality of Radiographic Clearance Measurements (P&WA/Connecticut)*

- Determine measurement accuracy deterioration due to high level of scatter radiation likely to be encountered in steel altitude test facility.
- Evaluate feasibility of reducing the effect of scatter radiation.
- Calculate the image resolution expected due to the geometry.
- Evaluate the feasibility of improving the geometry.

  1. Remove the X-ray source from the test chamber using low μ materials for windows.
  2. Extend side of chamber to add a "bubble" for source housing.

- Determine the maximum temporal resolution and the corresponding spatial resolution to be obtainable under the most feasible conditions.
- Determine whether these are consistent with the AEDC requirements.

1.4.6 *System Survivability (P&WA/Florida, Varian, and LMSC)*

- Determine effects of overpressurization on specific design of source, detector, and positioning system.
- Effects on evacuated tubes, i.e., magnetization, acceleration, and video tape.
- Determine the effect of impact by foreign objects on the X-ray source, position system, and detector system.
- Evaluate the effects due to repeated transportation of the system from location-to-location.
- Evaluate adverse environmental effects on the system.

1.4.7 *System Portability (P&WA/Florida, Varian, and LMSC)*

- Evaluate the feasibility of providing portable source and detector for interchangeability between cells.

- Investigate use of trailer-mounted control and power systems.
- Address the problem relative to positioning system including:

    1. Feasibility of using the same system on all test cells
    2. Feasibility of using portions of same system
    3. Details required to complement portability.

SECTION 2
X-RAY SOURCE REQUIREMENTS
(VARIAN ASSOCIATES, INC.)

2.0 INTRODUCTION

2.1 Summary

It was the purpose of Varian's program to study the feasibility of installing a high energy X-ray source in one or more of the altitude test cells (J-1, J-2, J-5, C-1, and C-2) at Arnold Engineering Development Center (AEDC), to produce real-time radiographs of turbine engines and rocket motors under operational conditions.

The performance requirements for the X-ray source were determined by considering the:

- Geometry and composition of the test objects
- Characteristics of the X-ray detectors
- Objective time and spatial resolutions.

The radiographic nature of the large rocket motors to be tested in the J-5 cell was different from that of the turbine engines and required a separate list of requirements.

A study was made of the trade-offs between spatial resolution, exposure time, radiation output, and physical size of the source. Consideration was given to space limitations in the individual test cells, and to possible modification of the cells to accommodate high-intensity sources.

Seven X-ray sources were evaluated for use in the test cells, ranging from standard "off-the-shelf" products to a new conceptual design. Three of these sources were recommended for the cell applications: the Varian LINATRON® 6000 for test cell J-5, the TELS[1] conceptual design for J-2 and C-1/C-2, and the LINATRON 3000 as an alternate for C-1/C-2.

2.2 General Design Requirements

2.2.1 *Requirements on the Radiographic System*

The system performance criteria set forth in the Statement of Work for this contract are as follows:

1. Time resolution: 60 film images in a 60-sec period. Also, a real-time imaging capability.

2. Spatial resolution: Clearance of 0.005 in., thickness variations of 0.020 in. (steel equivalent) with a total penetration of 3.5 in. of steel.

3. Portability: Equipment to be designed for movement from cell to cell.

4. Survivability: Equipment to be designed for minimum damage due to rupture of test article.

5. Health Standards: Operation must comply with applicable radiation health standards.

6. Physical constraints: Equipment must be physically compatible with positioning and operation in AEDC test cells J-1, J-2, C-1, C-2, and J-5.

2.2.2 *X-ray Source Requirements*

From a consideration of the system criteria of paragraph 2.2.1 and the characteristics of the X-ray detectors proposed, the following general design requirements for the X-ray source were developed:

2.2.2.1 *Turbine Engine Design Criteria:*

1. Bremsstrahlung spectrum — X-ray photon energies to 8 MeV

2. Bremsstrahlung flux — 3000 rad/min at 1m minimum on axis at maximum field angle (Radiation flux intensity is a function of field size, decreasing as the field angle is reduced.)

3. X-ray source shape — Circular

4. X-ray source diameter — Less than or equal to 1.0 mm

5. X-ray pulse width — Between 2 and 5 μsec

6. X-ray pulse rate — Variable from 50 to 350 pps

7. Total X-ray field angle — Adjustable from 8- to 1-deg total angle; 6- by 10-deg rectangular.

2.2.2.2. *Rocket Engine Design Criteria:*

1. Bremsstrahlung spectrum — X-ray photon energies to 15 MeV

2. Bremsstrahlung flux — 6000 rad/min at 1m minimum on axis at maximum field angle (Radiation flux intensity is a function of field size, decreasing as the field angle is reduced.)

3. X-ray source shape — Circular

4. X-ray source diameter — Less than or equal to 1.0 mm

5. X-ray pulse width — Between 2 and 5 μsec

6. X-ray pulse rate — 60 to 180 pps

7. Total X-ray field angle — Adjustable from 20- to 1-deg total angle; 15- by 20-deg rectangular.

2.3 Design Criteria

2.3.1 *Source Distance-Focal Spot Tradeoffs*

Where the source-to-object (SOD) distance is limited, as it is in the smaller test chambers, photographic image sharpness may be improved by reducing the focal spot size. This requires decreasing the electron beam current. (Current *density* is the factor which determines the target temperature rise.) The radiation flux produced is decreased in direct proportion to the beam current.

Radiation intensity varies inversely with the square of the distance from the source. Therefore, in order to obtain equal exposure times, the radiation output of a source must increase as the square of the source-to-film distance (SFD). Geometric unsharpness (U_g) is given by

$$U_g = \frac{S}{D/T} . \tag{5}$$

Where S is the diameter of the focal spot, D is the source-to-object distance, and T is the object-to-film distance (figure 9),

$$SFD = D + T. \tag{6}$$

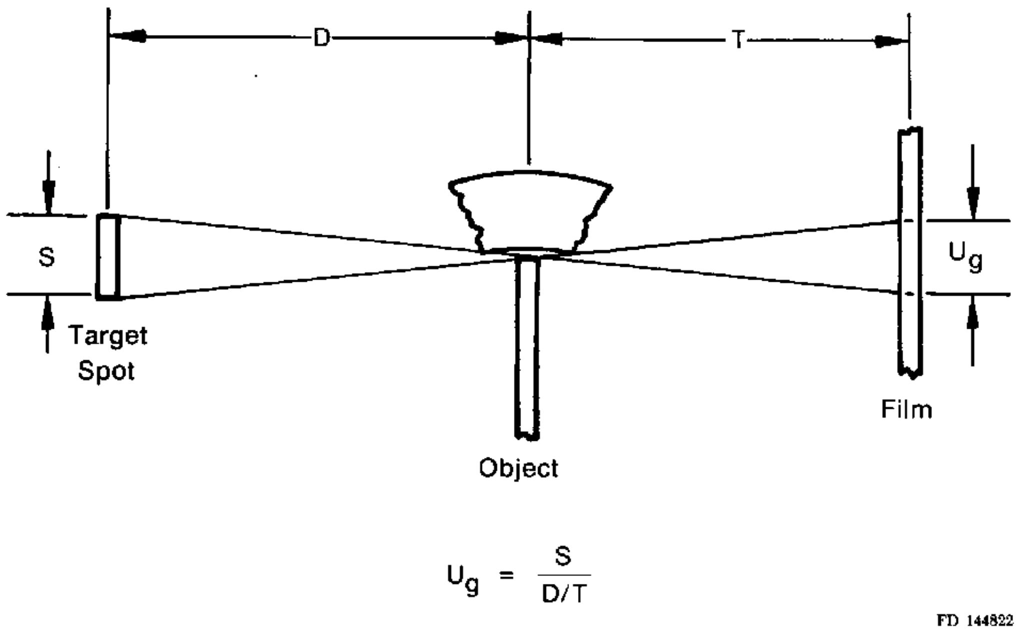


Figure 9. Geometric Unsharpness

If for a geometry with D = T initially, the SFD is doubled by increasing D while keeping the object-to-film distance T constant (figure 10), then

$$D_2 = 3\ D_1 \tag{7}$$

and

$$\frac{D_2}{T} = 3\ \frac{D_1}{T} .$$

The radiation intensity must be increased by a factor of 4 to maintain the same exposure time at the doubled SFD. If the X-ray target focal spot diameter was minimum for the original radiation

intensity, then it must be doubled to keep the same current density at the higher radiation intensity:

$$S_2 = 2\ S_1. \tag{8}$$

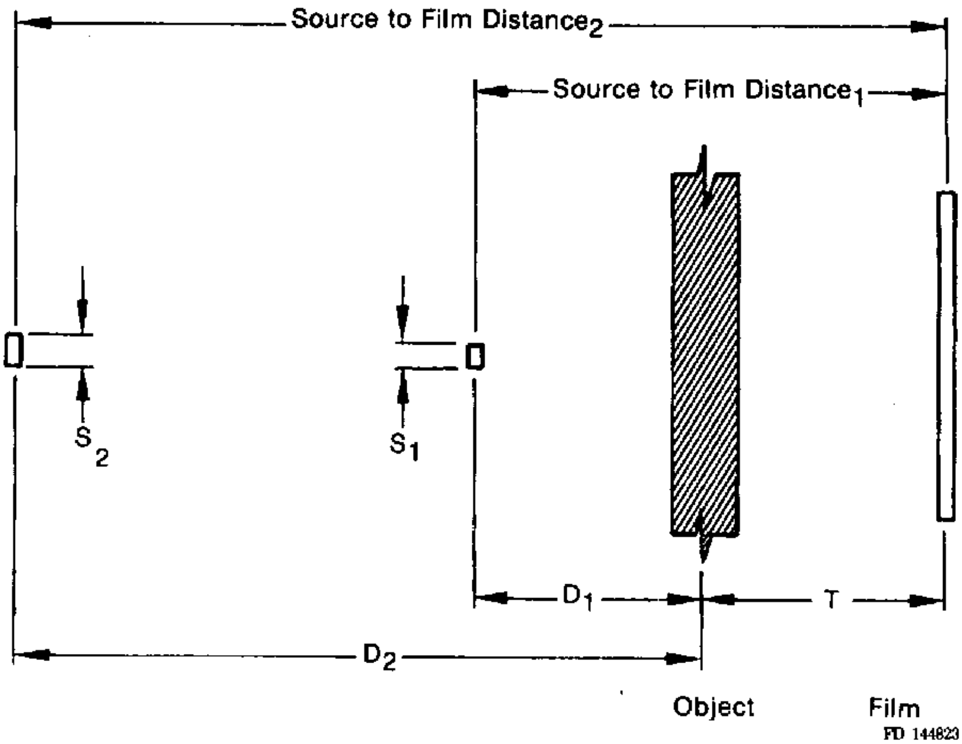


Figure 10. Effect of Object Distance on Unsharpness

The geometric unsharpness becomes

$$U_{g_2} = \frac{S_2}{D_2/T} = \frac{2\ S_1}{3\ D_1/T} = \frac{2}{3}\ U_{g_1}$$

so that unsharpness is *decreased* by moving the source away from the object. Conversely, the unsharpness is *increased* by moving closer to the object.

It must be noted that the gain in sharpness that can be realized by moving further away from the object is limited by other factors such as scatter and film-screen unsharpness, U_f. These latter limit the ultimate unsharpness to a value of about 0.6 mm at 10 MeV.[2]

These considerations indicate that with a fixed object-to-film distance, the image quality is optimized by locating the X-ray source as far as possible from the object consistent with physical limitations and generation of the required radiation intensity at the film.

2.3.2 Source Spot Size — Target Life Tradeoff

With solenoid focusing, a focal spot diameter of between 2 and 3 mm can generally be obtained for a long guide. In order to achieve further reduction it is necessary to use a magnetic quadrupole system near the target. The electron beam can be decreased by this means to a very small spot — so small that the target can be damaged. Target damage is caused by fatigue of the target metal due to thermal expansion caused by heating during the beam current pulses and contraction during the cooling between pulses. With the most efficient possible cooling, the surface temperature of the target button can rise several hundred degrees centigrade during a 3- or 4-μsec pulse. With pulse repetition rates of a few hundred per second the temperature cycling reaches steady-state condition within 10 pulses. Thus a fast-moving target can be used to keep the maximum local temperature below its ultimate steady-state value. The intrapulse temperature rise is proportional to electron beam current density and pulse length, and because of its high instantaneous value, is independent of the cooling geometry and the thermal conductivity of the target material. An ultimate limitation exists in which the temperature rise during a single pulse is sufficient to sputter metal from the surface. The result is very rapid erosion and an extremely short target life.

With a permanently mounted internal target, which must have a life of several thousand hours, the minimum spot size for X-ray sources producing radiation flux intensities of 3000 rad/min or more is about 1.5 mm. By using a nutating target the size can be reduced safely to 1.25 mm. To attain a 1.0-mm diameter it is necessary to design for a field-replaceable target, since the target life is reduced to about 40 beam hours.

The use of a replaceable target adds considerable complication to the output section of the accelerator guide. The target mounting space must be separated from the accelerating section by a vacuum-tight electron window or vacuum valve. The space between this window and the target must either be maintained during operation at a high vacuum, or a jet of nonoxidizing gas must be provided to prevent the generation of a plasma column.

Target life can be extended by programing the focusing quadrupole. One setting would provide the 1 mm focal spot diameter required for the highest resolution during test runs. A second setting would be used to produce a 2- or 3-mm spot. This setting could be used during the preliminary setup procedure, and for exposure calibration. The reduction in power absorption per

unit area at this setting permits extended operation with no damage to the target, and will hence greatly extend the useful target life. Fortunately a target operating at excessive power densities deteriorates gradually. The photographic image shows noticeable degradation a few hours before the target punches through. With this warning the target can be replaced well before it fails.

2.3.3 *Physical Constraints*

Additional criterion implicit in the general system requirements (paragraph 2.2.1) are the size and weight of the X-ray head. The space available in the test cells (particularly in J-1, J-2 and J-5) imposes limitations on the size of the head, particularly the axial length (in the direction of the X-ray beam). This length limitation in turn has a direct relation to the maximum energy and radiation output of the accelerator. The only ways to improve over an optimized accelerator in this respect are to increase the radio frequency (RF) power input to the guide, or to change the RF frequency of operation. Relative to the LINATRON 2000, the LINATRON 6000 employs the first approach; a high-power klystron is used, which greatly increases the size and weight of the X-ray head. The TELS-type system proposed employs the second approach; it would operate at an RF frequency of 5000 MHz instead of the frequency of 3000 employed in the LINATRON 2000 and 6000. (An exception to this is the LINATRON 3000 MHz proposed; this instrument, which is now in the preliminary design stage, will produce significantly greater radiation output, at a higher energy level, than the LINATRON 2000. This will be accomplished by the application of several design refinements to the accelerator guide, and by the use of a new improved magnetron as RF power source.)

The weight of the X-ray head and necessary local radiation shielding directly influence the design of the transport and positioning apparatus. These considerations are discussed elsewhere in the sections on radiation shielding and positioning systems, Sections 3 and 5, respectively.

2.4 X-RAY SOURCE SELECTION

2.4.1 Survey of Available Sources

This study began with the compilation of a list of available high-energy industrial radiographic sources[7]. When it became apparent that none of these sources even approximately met the requirements of this application, the list was extended first to include modification of one

of these units, and then to include a completely new system. This new system was developed conceptually in a previous study for the proposed TELS application.[1]

Seven sources were selected for preliminary evaluation:

1. The standard Varian LINATRON 2000, producing 2000 rads/min at 8 MeV (standard shielding only).

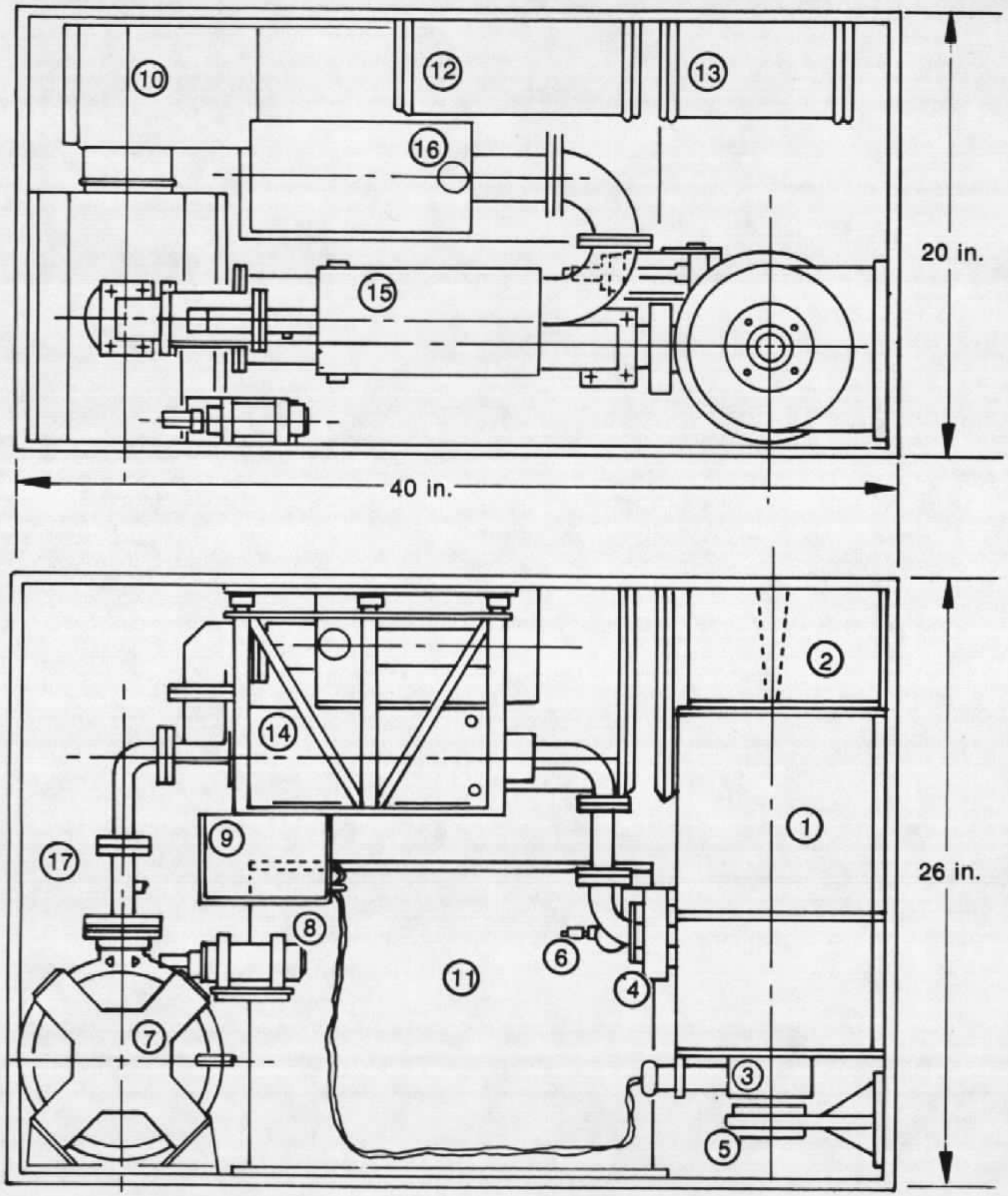
2. The LINATRON 3000, which is a design refinement of the LINATRON 2000 with a photon energy rating of 10 MeV and radiation output specification of 3000 rads/min at 1m minimum. It is scheduled for introduction in 1979. Data listed are for a LINATRON equipped with internal shielding and replaceable target.

3. The standard Varian LINATRON 6000, which develops 6000 rads/min at 15 MeV.

4. A proposed system conceptually designed for use on the Turbine Engine Loads Simulator centrifuge.[1] The X-ray source for this system possesses many of the qualities required in the test cell application — small size, high radiation output (3000 rads/min), ruggedness against shock and for operation in a high vibration environment, and protection against disintegration of the target. It is hereafter referred to simply as "the turbine engine load simulator (TELS) source." Data listed are for a head equipped with internal shielding and replaceable target.

5. "TELS Modified": This is the TELS system with the X-ray head physically modified to obtain minimum length in the direction of the X-ray beam axis, and with additional internal shielding to reduce leakage radiation in other directions (figure 11). Its performance specifications are identical with those of the TELS source.

6. The Super XX-6000. This is not a production machine; the prototype is presently under development. It is included, however, as it is the only portable source that might be available with output comparable to the Varian LINATRON 6000. The use of a "pretzel" beam bending magnet, which is offered as an optional accessory, is assumed in the tabulation to provide a means for evaluating the relative merits of the different geometry.



Accelerator Assy	1
Collimator	2
Gun	3
Window	4
Beam Stopper	5
Vacion Pump	6
Magnetron	7
AFC Motor	8
HV Switch	9
HV Connector	10
Pulse Transformer	11
Filament PWR Supply	12
Vacion PWR Supply	13
Circulator	14
Load No. 2	15
Load No.1	16
Coupler	17
Sound Barrier Foam	

FD 133993

Figure 11. TELS Modified Source

The manufacturer is Radiation Dynamics Ltd., a subsidiary of Radiation Dynamics Incorporated (standard shielding only).

7. The Mitsubishi ML 15R is a 3000 rad/min machine. Its performance is comparable to the Varian LINATRON 3000 but its size and weight are much greater than those of the Varian machine (standard shielding only).

The focal spot diameter in the above machines varies from 1.25 to 3 mm. For purposes of comparison a focal spot diameter of 1.0 mm or less has been assumed for all machines. This can be obtained in any of the Varian machines by the use of a short-lived, field-replaceable target.

As a first step in the source selection process, a matrix was developed showing the calculated performance of each source in each of the test cells. This matrix is given in Table 2. In the top part of this table the characteristics of each machine, derived from the published specifications, are listed. In the lower part of the table the calculated performance for the machine in each test cell is presented.

In the upper part of the table:

- Specified energy level and radiation output, and overall dimensions and weight are given for each machine. (The target spot size has been arbitrarily set at 1.0 mm for comparative purposes, as explained above).

- The half-value layers in steel, aluminum, and rocket propellant are given for the energy at which each machine operates. On the same lines the transmission for a 3.5-in. thick steel object, a 3-in. aluminum window, and a 12-in. thickness of propellant are indicated. These transmission factors are used in the calculation of exposure times in the column below.

- The film-screen unsharpness, which is a function of energy [2], is given for each machine.

In the lower part of the table machine performance is calculated for three conditions in each test cell:

- X-ray source mounted INSIDE the existing cell diameter (figure 12a). The source is located at the maximum SOD possible, in order to minimize the geometric unsharpness. A 6-in. space is allowed between the rear of the head and the cell wall for the positioning mount. A blank in this column indicates that there is insufficient space for internal mounting.

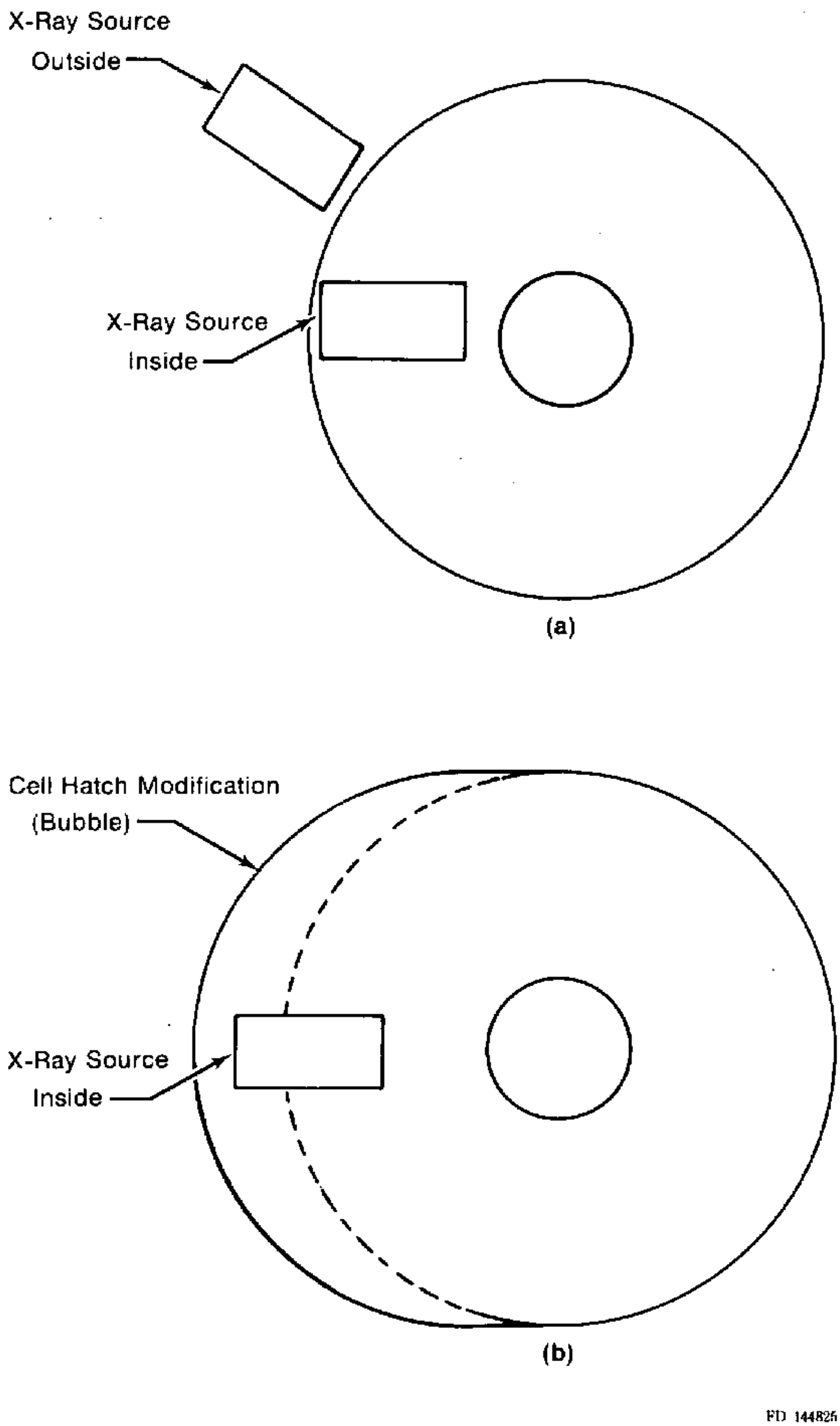


Figure 12. X-ray Source Position Options Show (a) Internal and External Source Mounts and (b) Internal Source With Bubble

TABLE 2. CALCULATED PERFORMANCE, ALTERNATE SOURCES

Machine		*Varian LINATRON® - 2000*	*TELS With Internal Shield*	*TELS - Modified*	*RDI Super XX 6000*	*Mitsubishi ML 15R*	*Varian LINATRON - 3000 With Internal Shield*	*Varian LINATRON - 6000*
Energy	MeV	8	8	8	12	12	10	15
Rads/Min at 1m	R/M/M	2000	3000	3000	6000	3000	3000 (tent)	6000
Target Dia	mm	1	1	1	1	1	1	1
Overall Length	in.	66	48	29	56 ***	123	80 ****	99
Height, Width	in.	29 × 28	32 × 24 ****	40 × 24 ****	124 (with pretzel)	34 × 28	40 × 40 ****	60 × 52
Weight	lb	2000	2400	2300	6600	6600	6000 ****	8300
HVL Steel → T(3½ in.)	in.	1.20 → 0.1324	1.20 → 0.1324	1.20 → 0.1324	1.28 → 0.1503	1.28 → 0.1503	1.26 → 0.1468	1.30 → 0.1547
HVL Alum → T(3 in.)	in.	3.90 → 0.5867	3.90 → 0.5867	3.90 → 0.5867	4.0 → 0.5946	4.0 → 0.5946	3.96 → 0.5915	4.10 → 0.6022
HVL Propellant → T(12 in.)	in.	5.90 → 0.2471	5.90 → 0.2471	5.90 → 0.2471	6.7 → 0.2688	6.7 → 0.2688	6.3 → 0.2584	7.60 → 0.2893
U_f	mm	0.55	0.55	0.55	0.64	0.64	0.60	0.67

Source Location		*Varian LINATRON® - 2000* Inside	Bubble	Outside	*TELS With Internal Shield* Inside	Bubble	Outside	*TELS - Modified* Inside	Bubble	Outside	*RDI Super XX 6000* Inside	Bubble	Outside
Test Cell J-1 (16-ft dia)				min	max		min	max	*min exp	min			min
Target-to-Object Distance	in.		90	108	49	100	111	63	41	107		120	116
SFD	in.		126	144	85	136	147	99	77	143		156	152
Geom. Unsharpness (U_g)	mm		0.4	0.3	0.7	0.4	0.3	0.6	0.9	0.3		0.3	0.3
Total Unsharpness (U_t)	mm		0.6	0.6	0.8	0.6	0.6	0.7	0.9	0.6		0.7	0.7
Exposure Time	sec		3.5	7.8	1.1	2.7	5.2	1.4	0.9	5.1		1.6	2.5
Bubble Radius	ft		13.7			11.5			**			15.7	
Test Cell J-2 (20-ft dia)		max		min	max	*min exp	min	max	*min exp	min	max		min
Target-to-Object Distance	in.	51	90	132	75	45	135	88	41	131	52	120	140
SFD	in.	87	126	168	111	81	171	124	77	167	88	156	176
Geom. Unsharpness	mm	0.7	0.4	0.3	0.5	0.9	0.3	0.4	0.9	0.3	0.7	0.3	0.3
Total Unsharpness	mm	0.8	0.6	0.6	0.7	0.9	0.6	0.6	0.9	0.6	0.8	0.7	0.7
Exposure Time	sec	1.7	3.5	10.5	1.8	1.0	7.3	2.2	0.9	6.9	0.5	1.6	3.4
Bubble Radius	ft		13.7			**			**			15.7	
Test Cells C-1, C-2 (28-ft dia)		max		min	max	*min exp	min	max	*min exp	min	max		min
Target-to-Object Distance	in.	95		180	125	45	183	137	41	179	138	188	188
SFD	in.	131		216	161	81	219	173	77	215	174	224	224
Geom. Unsharpness	mm	0.4		0.2	0.3	0.9	0.2	0.3	0.9	0.2	0.3	0.2	0.2
Total Unsharpness	mm	0.6		0.6	0.6	0.9	0.6	0.6	0.9	0.6	0.7	0.6	0.6
Exposure Time	sec	3.8		17.4	3.8	1.0	11.9	4.4	0.9	11.5	1.9	3.2	5.4
Bubble Radius	ft		**			**			**				
Test Cell J-5 (16-ft dia)				min	max		min	max	*min exp	min			min
Target-to-Object Distance	in.		90	108	49	100	111	63	46	107		90	116
SFD	in.		133	151	92	143	154	108	89	150		133	159
Geom. Unsharpness	mm		0.5	0.4	0.9	0.4	0.4	0.7	0.9	0.4		0.5	0.4
Total Unsharpness	mm		0.7	0.6	0.9	0.6	0.6	0.8	1.0	0.6		0.7	0.7
Exposure Time	sec		2.1	4.6	0.7	1.6	3.4	0.9	0.6	3.0		0.6	1.5
Bubble Radius	ft		13.7			11.5			**			13.5	

Source Location		*Mitsubishi ML 15R* Inside	Bubble	Outside	*Varian LINATRON - 3000 With Internal Shield* Inside	Bubble	Outside	*Varian LINATRON - 6000* Inside	Bubble	Outside
Test Cell J-1 (16-ft dia)				min			min			min
Target-to-Object Distance	in.		120	116		78	116		120	122
SFD	in.		156	152		114	152		156	158
Geom. Unsharpness (U_g)	mm		0.3	0.3		0.5	0.3		0.3	0.3
Total Unsharpness (U_t)	mm		0.7	0.7		0.7	0.6		0.7	0.7
Exposure Time	sec		3.1	5.0		1.8	5.2		1.5	2.6
Bubble Radius	ft		20			13.7			17.5	
Test Cell J-2 (20-ft dia)				min	max		min			min
Target-to-Object Distance	in.		120	140	45	78	140		120	146
SFD	in.		156	176	81	114	176		156	182
Geom. Unsharpness	mm		0.3	0.3	0.8	0.5	0.3		0.3	0.2
Total Unsharpness	mm		0.7	0.7	0.9	0.7	0.6		0.7	0.7
Exposure Time	sec		3.1	6.7	0.9	1.8	7.0		1.5	3.4
Bubble Radius	ft		20			13.7			17.5	
Test Cells C-1, C-2 (28-ft dia)		max		min	max		min	max		min
Target-to-Object Distance	in.	53		188	90		188	80		194
SFD	in.	89		224	126		224	116		230
Geom. Unsharpness	mm	0.7		0.2	0.4		0.2	0.5		0.2
Total Unsharpness	mm	0.8		0.6	0.7		0.6	0.7		0.7
Exposure Time	sec	1.0		10.9	2.1		11.3	0.8		5.5
Bubble Radius	ft		**			**			**	
Test Cell J-5 (16-ft dia)				min			min			min
Target-to-Object Distance	in.		116	116		78	116		90	122
SFD	in.		159	159		121	159		133	165
Geom. Unsharpness	mm		0.4	0.4		0.6	0.4		0.5	0.4
Total Unsharpness	mm		0.7	0.7		0.7	0.7		0.7	0.7
Exposure Time	sec		1.8	3.1		1.1	3.4		0.6	1.5
Bubble Radius	ft		20			13.7			15	

*Positioned for minimum exposure time
**Bubble not required
***Dimensions estimated
****Weight and volume of these machines have approximately doubled due to added internal shielding and replaceable target

Max = Max TOD attainable inside cell
Min = Min TOD attainable outside cell

- X-ray source mounted inside the test cell, but with an external *bubble* on the cell wall to permit locating the source at the optimum distance for minimum image unsharpness (Figure 12b). Those cases in which the addition of a bubble is not necessary are indicated by two asterisks in the "bubble radius" position. In six cases (in the TELS and TELS modified columns) where the bubble is not required, performance is listed for the source located as close to the object as possible to produce minimum exposure time. These entries are headed MIN. EXP.

- X-ray source mounted OUTSIDE the existing cell with a 3-in. aluminum window in the cell wall (Figure 12a). A 6-in. clearance is allowed between the source enclosure and the cell wall.

The following assumptions were used in the calculations:

1. 1.5 rads are required at the film plane for exposure.

2. Maximum diameter of engine under test (including external piping, etc.): 60 in. for turbine engine, 92 in. for rocket motor.

3. Object thickness: 3.5 in. of steel in J-1, J-2, C-1, C-2; 12 in. of propellant in J-5.

4. Window, 3.0-in. thickness of aluminum.

5. Object to film distance, 36 in. for turbine engine, 46 in. for rocket motor.

6. Clearance required around X-ray head for positioning equipment, 6 in.

7. Dimensions of RDI Super-XX head were estimated from a preproduction conceptual drawing.

A typical calculation of X-ray source performance is given below. This case is for the TELS modified source installed in test cell J-1.

1. Transmission factors

- For steel, half value layer = 1.20 in. at 8 MeV

  Transmission through 3.5 in. of steel:

$$T = 0.5_{\epsilon}^{\frac{\ell}{\mathrm{HVL}}} = 0.5_{\epsilon}^{\left(\frac{3.5}{1.20}\right)} = 0.1324 \qquad (10)$$

- For aluminum (window), HVL = 3.90 in.

  Transmission through 3.0 in.:

$$T = 0.5_{\epsilon}^{\left(\frac{3.0}{3.90}\right)} = 0.5867 \qquad (11)$$

- For propellant, HVL = 5.90 in.

  Transmission through 12 in.:

$$T = 0.5_{\epsilon}^{\left(\frac{12}{5.90}\right)} = 0.2471 \qquad (12)$$

2. Film-screen unsharpness

$$U_F = 0.55 \text{ mm at } 8 \text{ MeV}^{[2]} \qquad (13)$$

3. Target-to-Object Distance (TOD)

- For inside cell mounting (first column) maximum distance determined by layout, with 6-in. clearance between rear of head and inside chamber wall. Target is located 5 in. from front surface of head.

  TOD = 63 in.

- Bubble mounting (second column). Since a bubble on the cell wall is not required to mount the modified TELS head inside this test cell, this column was used to indicate performance when the head is located to permit minimum exposure time (i.e., positioned as close to the object as

possible); in this case, with a 6-in. clearance to the outer surface of the engine.

TOD = 41 in.

- Outside cell mounting (third column) 6-in. distance between front of head and inside chamber wall.

TOD = 107 in.

4. Source-to-Film Distance (SFD)

With an object-to-film distance (OFD) of 36 in.

SFD = TOD + 36 in. = 63 + 36 = 99 in.

(From this point, only the inside cell mounting, given in the first column will be calculated in detail.)

5. Geometric unsharpness (U_g)

$$U_g = \frac{S}{D/T} = \frac{1.0}{63/36} = 0.57 \text{ mm} \tag{14}$$

S = focal spot diameter
D = TOD
T = OFD

6. Total unsharpness (U_t)

$$U_t = \sqrt[3]{U_f^3 + U_g^3} \tag{15}$$

$$= \sqrt[3]{(0.55)^3 + (0.57)^3} = 0.71 \text{ mm}$$

7. Exposure time

Radiation intensity at film:

$$I_{film\ plane} = \frac{I_{machine}}{(SFD)^2} \times T_{steel} \times T_{window} \tag{16}$$

$$= \frac{3000 \times 0.1324 \times 1}{(99 \times 0.0254)^2}$$

$$= 62.8 \text{ rads/min}$$

(Note that SFD must be converted to meters since $I_{machine}$ is given in rads/min at 1m.)

- Exposure time

$$t = \frac{R_{exp}}{I_{film\ plane}} = \frac{1.5}{62.8} \times 60 = 1.43 \text{ sec} \tag{17}$$

R_{exp} = radiation dose required at film for exposure
= 1.5 rads

2.4.2 Selection of Sources

Using the source performance matrixes of Table 2, a basic factor analysis was completed for each of the cells — J-2 (table 3), C-1/C-2 (table 4) and J-5 (table 5) — as one approach in the source selection process. Only the combination of sources with test cells from table 2 were used in these analyses. The factors selected were a combination of quantitative (U_g, exposure time, cost, etc.) and qualitative (cell modification and positioning capability) "attributes." Each "attribute" is weighted based on the analyzer's considered importance of the factors being used.

TABLE 3. FACTOR ANALYSIS WORK SHEET (J-2)

Excel = 4
Good = 3
Fair = 2
Poor = 1

Factor	Weight Factor	L-2000 Inside Chamber With Bubble (With Vault)	L-3000 Inside With Bubble (With Internal Shielding)	TELS Inside Chamber	TELS With Bubble	
Source-to-Engine Distance, in. (TOD) (max)	5	90 / 3 / 15	78 (opt.) / / 5	75-45 / 1 / 5	88-45 / 2 / 10	
Geometric Unsharpness mm (U_g)	10	0.41 / 3 / 30	0.47 / 3 / 30	0.50 / 3 / 30	0.9 / 3 / 30	
Total Unsharpness mm (U_t)	10	0.62 / 3 / 30	0.68 / 3 / 30	0.70 / 3 / 30	0.963 / 3 / 30	
Cell Modifications (Bubble)	20	Yes / 1 / 20	Yes / 1 / 20	No / 4 / 80	Yes / 1 / 20	
Exposure Time (sec)	10	3.5 / 1 / 10	1.8 / 2 / 20	1.8-1.0 / 4 / 40	2.3-1.0 / 4 / 40	
Cost of Source*	5	X / 3 / 15	2X / 2 / 10	4X / 1 / 5	4X / 1 / 5	
Positioning Capability	15	Poor / 1 / 15	Fair / 2 / 30	Good / 3 / 45	Good / 3 / 45	
Total Points		135	145	235	180	
Ranking		4	3	1	2	

Actual Data / Score / Total Points (Score × wt)

*X = base cost

TABLE 4. FACTOR ANALYSIS WORK SHEET (C-1/C-2)

Excel = 4
Good = 3
Fair = 2
Poor = 1

Cell entries: Actual Data / Score / Total Points (Score × wt)

Factor	Weight Factor	L-2000 (With Vault) Inside Chamber	L-2000 (With Shield) Inside Chamber	TELS (With Shield) Inside Chamber		
Source-to-Engine Distance, In. (TOD) (max)	5	95 / 3 / 15	90 / 3 / 15	125 / 4 / 20		
Geometric Unsharpness mm (U_g)	10	0.4 / 3 / 30	0.4 / 3 / 30	0.3 / 4 / 40		
Total Unsharpness mm (U_t)	10	0.6 / 4 / 40	0.7 / 3 / 30	0.6 / 4 / 40		
Cell Modifications (Bubble)	20	None / 4 / 80	None / 4 / 80	None / 4 / 80		
Exposure Time (sec) (Min. Possible)	10	3.8 / 1 / 10	2.1 / 1 / 10	1.0 / 4 / 40		
Cost of Source*	5	X / 3 / 15	X / 2 / 10	4X / 1 / 5		
Positioning Capability	15	Poor / 1 / 15	Good / 3 / 45	Excellent / 4 / 60		
Total Points		205	245	285		
Ranking		3	2	1		

*X = base coat

TABLE 5. FACTOR ANALYSIS WORK SHEET (J-5)

Excel = 4
Good = 3
Fair = 2
Poor = 1

Each cell: Actual Data / Score / Total Points (Score × wt)

Factor	Weight Factor	L-6000 (Outside)	RDI Super XX 6000 (Outside)			
Source-to-Engine Distance, In. (TOD) (max)	5	122 / 4 / 20	116 / 3 / 15			
Geometric Unsharpness mm (U_g)	10	0.3 / 4 / 40	0.3 / 4 / 40			
Total Unsharpness mm (U_t)	10	0.7 / 4 / 40	0.7 / 4 / 40			
Cell Modifications (Bubble)	20	No / 4 / 80	No / 4 / 80			
Exposure Time (sec)	10	1.5 / 1 / 10	1.5 / 1 / 10			
Cost of Source*	5	X / 3 / 15	X / 3 / 15			
Positioning Capability	15	3 / 45	3 / 45			
Total Points		250	245			
Ranking Number		1	2			

*X = base cost

Following this, each factor was scored from "excellent" (4) to "poor" (1) and points calculated by multiplying the weight factor × score. It should be noted that there was some redundancy in the factors (exposure time and unsharpness factors are proportional in part to the source-to-engine distance) and that weighting and scoring are judgment decisions. Also, other factors could enter into the comparison and selection of a source, e.g., radiation shielding needed, availability of equipment, portability, etc., that have not been used in the base deductions arrived at through factoring. These analyses make clear one point: no single source can be selected for optimum performance in all facilities. The LINATRON 6000 most nearly meets all of the operating requirements noted in paragraph 2.2.1 for turbine and rocket engines. Its use in the turbine test cells would, however, have the following disadvantages:

1. Either a large personnel exclusion radius (120 to 180m) would be required, or a lead shielding vault (10,00 to 20,000 kg) would be required.

2. Positioning flexibility is severely restricted by the lack of room for internal positioning in cell J-2. External positioning increases the exposure time to an unacceptable level.

3. The large size and weight of the X-ray head and vault would put severe requirements on support and positioning equipment for internal mounting in test cells C-1 and C-2. The large size and close proximity to the engine would also impact free jet testing.

2.4.2.1 X-ray Source for Turbine Engine Testing

Three sources were considered in some detail for use in the turbine engine test cells: the LINATRON 2000, the LINATRON 3000, and the TELS source.

- The LINATRON 2000

  This is the "off-the-shelf" source that best meets the requirements for these test cells. It can be used internally in all three locations, thus taking advantage of the radiation shielding of the cell walls, and avoiding the additional scattered radiation that is generated by transmitting the beam through a window in the cell wall. Since its size permits very little flexibility of positioning in cell J-2, it would require the addition of a large bubble on the cell wall. With a bubble of radius 13.7 ft from the cell axis, a total image unsharpness of 0.6 mm, about the smallest figure achievable, could be obtained.

A disadvantage of this source is its low radiation flux, which requires long film exposure times. At its closest location to the test object, the exposure time is 1.5 sec; at this spacing the image resolution has degraded by 50% (to an unsharpness of 0.9 mm). At a spacing of 90 in., required to realize an unsharpness of 0.6 mm, the exposure time is increased to 3.5 sec.

An additional problem arises with respect to leakage radiation. Direct leakage from the X-ray head is great enough that a personnel exclusion radius of about 76m would be required. This radius could be reduced to an acceptable figure by added local shielding, either a *lead vault* enclosure or *internal shielding* around the accelerator guide. The lead vault is unattractive because it adds about 10T to the loading of the positioning equipment. The addition of sufficient internal shielding to eliminate the requirement for the vault would offset the advantage this source offers as standard production equipment, as it would require a complete redesign of the X-ray head.

Evaluation of the LINATRON 2000 for use in test cells C-1 and C-2 is essentially the same as for J-2, with the exception that the bubble on the cell wall would not be required.

The LINATRON 2000 is not recommended for this application for the following reasons:

- It has marginal measurement capabilities due to its low radiation flux.
- Extensive modifications to test cell J-2 would be required for its use at that location.
- The shielding required to reduce leakage radiation to an acceptable level would result in either excessive size and weight or a large increase in cost.

- The LINATRON 3000

This source has 50% more radiation flux than the LINATRON 2000. In most other respects it is very similar to that machine. With its higher output flux it reduces the exposure times in cell J-2 to 0.9 sec for close-mounting to the

engine (0.9 mm total unsharpness) and 1.8 sec with a 13.7-ft radius bubble (0.7 mm total unsharpness).

Offsetting the advantage of superior radiographic performance is the fact that this is not an established commercial product. Exact performance specifications, physical characteristics, and costs have not been fully established. Also, the thickness of shielding material required to reduce leakage to a tolerable level is increased because of the higher output flux. The cost differential between this source and the LINATRON 2000 may not be as great as one would expect, if internal shielding is used in both cases to reduce leakage radiation. If this were done, both machines would require a complete mechanical redesign.

Indeed, the cost and size of any commercial machine when modified to operate in the test cells will be significantly increased. The addition of internal radiation shielding requires a complete redesign of the X-ray head and guide support structure. It is necessary to seal and pressurize the X-ray head to prevent corona discharge around high-voltage terminals under high-altitude conditions, and to provide adequate air cooling for high-voltage circuit components. Further, the addition of a replaceable target and fine-focusing system to any standard source involves added size and expense.

For service in test cells C-1 and C-2, the LINATRON 3000 provides satisfactory radiographic performance, a range of total unsharpness from 0.6 mm (at 3.2-sec exposure time) to 0.9 mm (at a 0.9-sec exposure).

The LINATRON 3000 is selected only as a *second choice* for use in the turbine engine test cells for the following reasons:

1. Extensive modification of test cell J-2 would be required for its use.

2. The shielding required to reduce leakage radiation to an acceptable level would result in either excessive size and weight or a large increase in cost.

3. It is not at present a standard "off-the-shelf" product.

- The TELS Source

The TELS source, as proposed, produces the same radiation flux as the LINATRON 3000, but with the lower energy of the LINATRON 2000. This combination of properties gives it a slight radiographic advantage; the higher flux permits the shorter film exposure times offered by the LINATRON 3000, but the lower energy of 8 MeV results in a film-screen unsharpness (which determines the ultimate limitation on image sharpness) 10% less than that of the LINATRON 3000. The difference in penetration of steel between 8 and 10 MeV energy levels is negligible. As a consequence, it can produce film images with a total unsharpness ranging from 0.6 to 0.9 mm in any of the test cells, at exposure times between 2.7 and 0.9 sec. Due to the smaller size of the X-ray head, no sidewall bubble is required on cell J-2.

The size and weight of the TELS X-ray head are substantially less than the LINATRON 2000 or 3000. This means not only that the range of positioning possibilities in the test cells is much greater, but also that the requirements on the positioning equipment are much less severe. The head support structure, being a new design, can be constructed initially to accommodate an internally shielded accelerator guide (Section 3). With this internal shielding the leakage radiation is reduced sufficiently to permit operation with personnel within 30m of the cell. An external vault is not required, and the total weight of the X-ray head is on the order of 1T.

The major disadvantage of this source is that it is presently in the conceptual design stage. A sizeable investment of time and money will be required for its development.

The TELS source is recommended for use in the turbine engine test cells for the following reasons:

1. It provides adequate radiographic performance.

2. No major modifications are required in test cells J-2, C-1 or C-2 to permit its use.

3. The design, as proposed, includes internal radiation shielding of the accelerator in lieu of an external vault for leakage radiation.

4. The size and weight of the X-ray head are relatively small. This permits the use of less massive and more versatile positioning equipment.

5. Most components, and possibly the entire head, are common to the equipment proposed to be installed on the TELS centrifuge.

6. Being designed for small size, mechanical ruggedness and easy portability, a single set of equipment can be used in all three test cells. Movement from cell-to-cell is relatively easy.

2.4.2.2 X-ray Source for Rocket Engine Testing

The large rocket engines to be tested in cell J-5 require much higher energy levels and radiation flux than the turbine engines to be tested in the other cells. Of all the sources considered, only the two producing 6000 rads/min are adequate for this application.

- The Super XX 6000

  This is a high intensity, high-energy radiographic linear accelerator under development by Radiation Dynamics, Limited. It is rated at 6000 rads/min at 12 MeV, or 5000 rads/min at 14 MeV. As a special option, a quadrupole beam focusing system is offered to reduce the focal spot diameter to less than 1.5 mm.

  Another option is a 90-deg bending magnet that can be used to bend the output through a right angle with respect to the accelerator axis. This feature offers the possibility of mounting the X-ray head inside of the larger test cells, as the radial dimension of the head is reduced. Unfortunately, there is insufficient space in cell J-5 to take advantage of this capability.

  The Super XX is not recommended for use in cell J-5 for the following reasons:

  1. The energy spectrum limited to 12 MeV suffers about 10% more attenuation in rocket propellant than the 15 MeV energy of the LINATRON 6000.

2. The use of a bending magnet requires, in general, significantly increased complexity, and therefore an increased probability of system failure.

3. No production model has been released to date.

- The LINATRON 6000

  This is an established high-energy source, which was introduced about 4 years ago. It produces over 6000 rads/min at a maximum energy level of 15 MeV. The X-ray head is somewhat larger and heavier than the Super XX, but the system is less complex.

  The remote location and earth barrier shielding of cell J-5 eliminate the requirement for additional shielding. This means the LINATRON 6000 can be used essentially as produced at this site.

  An available option of this machine is a nutating target and quadrupole focusing system to reduce the focal spot size to less than 1.5 mm. This structure is adaptable to accommodate a replaceable target assembly. Mounted outside of cell J-5, this source would produce a total unsharpness of 0.7 mm, with an exposure time of 1.5 sec for a propellant thickness of 12 in.

  The LINATRON 6000 is recommended for use in cell J-5 for the following reasons:

  1. The 15-MeV energy spectrum provides superior penetration of solid propellants.

  2. The focal spot is circular, and can be reduced to 1 mm diameter.

  3. This model is in current production.

2.4.2.3 Description of the Equipment Recommended

Current specifications for the Varian LINATRON 2000 and LINATRON 6000 are given in Appendix A. A summary specification is also given for the proposed TELS source. The standard LINATRON 3000 will be physically similar to the LINATRON 2000; overall length of the X-ray head will be slightly greater. The addition of internal shielding, field-replaceable target, and head

pressurization will produce some changes in size and weight of the X-ray heads. Standard modulators and control stations can be used in these applications.

The LINATRON 3000, modified in the above respects, would increase in weight to 6000 lb, and in size to approximately 80 by 40 by 40 in. While incorporation of quadrupole focusing coils and a replaceable target is responsible for a 10-in. increase in length, the increased size and weight are primarily due to the additional internal radiation shielding.

The TELS source with internal shielding and a replaceable target would weigh about 2400 lb. Its length would be 48 in., and its height and width 32 by 24 in. With these changes the focal spot size will be reduced to less than 1.0 mm.

2.5 Additional System Considerations

2.5.1 Survivability

It would be impossible to design an accelerator X-ray head to be immune to damage resulting from the failure of an engine under test. Certain obvious measures can, however, be taken to protect the more vulnerable and expensive components. The original TELS head was designed with these considerations in mind. The frontal area is made as small as practical. The front plate and the side wall that serve as the principal mounting base are made of heavy steel plate. The accelerator guide and the magnetron, the two highest cost components, are mounted to this common mounting base, with the magnetron to the rear of the guide.

The accelerator guide in any conventional head is shielded from objects approaching along its axis by the collimator. This is usually made from lead or tungsten and is several inches thick with a small hole directly in front of the target. The focusing solenoid, a multilayer coil of heavy copper wire, provides a certain amount of protection to the lateral surfaces of the guide. When an internal radiation shield of the type discussed in this report is used, the guide is completely surrounded by a cylindrical tube, several inches thick, of a heavy material such as lead, tungsten, or uranium. This provides very good protection against small particles.

The magnetron possesses little inherent shielding. It must be protected by location, and by whatever shielding can be added in the structure. Since the performance of this tube can be degraded by distortion of its magnetic field, it is necessary to use only nonmagnetic materials for its support and protection. The RF power source in the LINATRON 6000 is a klystron, which is larger and more expensive than the magnetron. The klystron is mounted vertically in the cabinet, so unfortunately, it presents a rather large target cross section to flying debris. It is partially

covered by a focus solenoid and its pulse transformer, which would afford limited protection against small projectiles.

The LINATRON 6000, because of its high-energy level and radiation output, is heavily shielded to reduce leakage radiation. This shielding consists of multiple layers of steel plates around the target region of the accelerator guide, and from 6 to 12 in. of solid polyethylene in the front and lateral surfaces of the cabinet. The purpose of the polyethylene is to absorb neutron radiation produced by the high-energy photons. In this application it should prove beneficial also as a shield against metal fragments.

All Varian LINATRONS, as well as the proposed TELS source, are constructed in heavy steel frames. These frames afford protection from damage by large nonpenetrating bodies. This protection is, of course, limited to impacts that do not result in frame distortion, as the alignment of many components in the head is critical for proper operation.

The more sensitive components in the X-ray head of the TELS source are to be supported by stiff compliant mountings, primarily in order to provide isolation from frame-transmitted vibration. This mounting also provides protection against shock caused by the impact of large objects on the external case.

In case of damage to the X-ray head or cables that in any way impair the operation of the cooling, pressurization, or high voltage circuits, the high voltage supply and the RF source are immediately shut down. This prevents further damage to any component due to continued operation. An interlock connection can also be used to shut the system down prior to actual damage by sensing abnormal operation of the test engine (such as excessive vibration or mount stresses, for example).

It may be said in conclusion that the X-ray sources considered, in particular the TELS source and the LINATRON 6000, possess some inherent protection against catastrophic failure of the test engine. This consideration was a factor in the design of the TELS head. Such protection can be increased in the LINATRONS by the addition of frontal shielding plates. The impact on weight and cost will be minor compared with that of providing internal radiation shielding.

2.5.2 Portability

Portability, as applied to the X-ray source, implies that the X-ray head is small and light enough to be conveniently handled by existing gantry cranes, forklifts, and trucks in and between the test cell areas, trailer-mounted or easily moved power supply-modulators, and means for

installing and connecting the X-ray system and its control console at any test site within one working day. The components of the system, particularly the X-ray head, must be designed to withstand the shocks and vibration experienced in crane handling and transportation.

The TELS system clearly meets these requirements. The X-ray head is designed to withstand high-intensity vibration. Components are shock-mounted in a rugged enclosure which also excludes dust and rain. Its size and weight permit easy handling, loading, and unloading (figure 13).

The LINATRON X-ray heads, while not so light and compact as the TELS head, are also designed for portability. In normal service they are positioned by cranes, elevators, carts, and forklifts. (See Appendix C.)

For all of the systems recommended, the modulators are larger and less rugged than the X-ray heads. These units are normally installed on a semipermanent basis at a fixed location in a factory building. Since they may be located at a distance of several hundred feet from the X-ray head, they can conveniently be installed in a trailer which is moved to a location adjacent to the test cell being used.

The control console may be located in the trailer with the modulator, or it may be located in the test site control room. This component is small, light, and easily carried from site-to-site. Aside from the main power switch and circuit breaker panel, which are located in the modulator cabinet, all system functions are controlled from the control console. It may be located several hundred feet from both the X-ray head and the modulator. It monitors the operation of the system, indicating operational status, radiation output rate, and interlock and fault conditions.

Cell change time can be minimized by permanently installing a set of interconnecting cables at each test cell. Equipment installation then only requires mounting of the X-ray head, installation of the control console, and connection to the modulator at the trailer parking place.

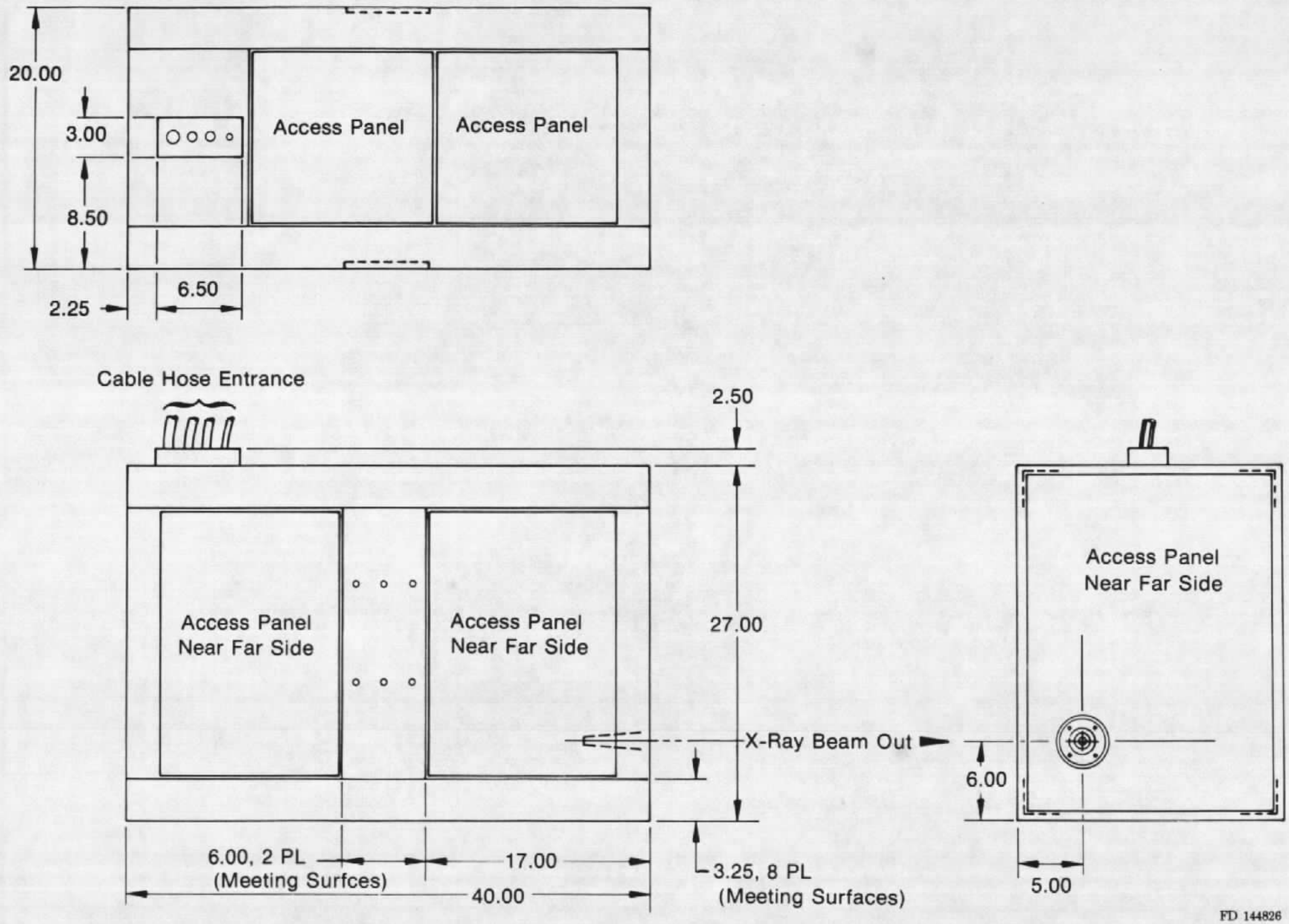


Figure 13. TELS X-ray Head Cabinet

SECTION 3
PERSONNEL SAFETY AND RADIATION SHIELDING
(VARIAN ASSOCIATES, INC.)

3.0 INTRODUCTION

X-ray accelerator requirements for turbine engine and rocket motor radiography at AEDC have been presented in Section 2.0, X-ray Source Requirements. As a result, the LINATRON® 6000 was the recommended source for test cell J-5 applications with the proposed Turbine Engine Loads Simulator (TELS) X-ray accelerator recommended for cell J-2 and cell C-1/C-2 applications. At the same time, the LINATRON 3000 was considered as a backup for the TELS source at C-1/C-2.

This section addresses the shielding requirements for these sources when installed at their respective test cells. Calculations for shielding thickness and the location of personnel protection barriers are presented. The shielding configurations presented are judged to be the most practical, considering the many restraints imposed on shielding design, particularly for cells C-1/C-2 and J-2.

In these cases, the X-ray source must be installed in existing or predesigned facilities with insufficient space to provide complete shielding enclosures. As a result, controlled area perimeters are required which must be completely isolated from all personnel during X-ray operation. The impact of evacuating test personnel working from portions of the building occupied by the test cell and from adjoining areas has not been investigated. Because of the complexity of the test area layouts and the high density of occupied area surrounding these buildings, no other alternatives were available. Permanently installed radiation shielding such as some of the building walls and floors and some portions of inlet and exhaust ducting not considered in this study may allow further reduction on some of the restrictions presently imposed. Follow-on studies should consider these points in more detail.

3.1 General Shielding Design Considerations

3.1.1 Shielding for Leakage Radiation

Design requirements for turbine engine testing to be performed in test cells J-2 and C-1/C-2 require an X-ray source with energies to 10 MeV and a minimum output of 50 rad/sec at 1m or 3,000 rad/min. Two possible sources have been considered for this application; namely, the TELS and the LINATRON 3000 X-ray linear accelerators. TELS is a compact 8-MeV X-ray source, designed but not presently available. The LINATRON 3000 is an upgraded version of Varian's LINATRON 2000 8-MeV X-ray linear accelerator which has been used by Pratt & Whitney

Aircraft in turbine engine radiographic studies at their Connecticut facilities. The LINATRON 3000 will operate at an increased X-ray energy of 10 MeV and an increased output of 3000 rad/min. Its outer dimensions will be identical to that of the LINATRON 2000. The TELS X-ray system as recommended in Section 2, will be used in J-2, while the LINATRON 3000 will be used in test cells C-1/C-2 for determining shielding requirements.

Radiographic X-ray units are conventionally shielded so that leakage radiation at 1m is reduced to 0.001 of the primary beam intensity at the same distance. Auxiliary shielding for leakage radiation is then provided by means of a complete enclosure, in most cases with concrete walls with a substantially thicker wall for the primary beam. Ceilings may or may not be shielded, depending on the requirements imposed by adjoining facilities.

Because it is impractical to provide complete shielding for the altitude test cells, it was considered expedient to reduce leakage radiation by as much as two additional tenth-value layers (TVL), thereby restricting the leakage to transmission to 10^{-5} of the primary beam.

Leakage radiation includes all radiation emitted from the tube housing other than the primary beam. Leakage radiation may be considered as isotropic. A complete shielding enclosure of uniform thickness (plus primary barrier) is required whenever the dose rate at a given distance from the target must be reduced to a given level.

For TELS and the LINATRON 3000, the leakage dose rate at 1m is 1.8×10^5 mrad/hr or 1.8×10^3 mrad/hr at 10m. This dose rate is reduced to 600 mrad/hr at 10m by the 2-in. thick steel walls provided by the test cells.

It is desirable to determine the distance at which the dose rate is reduced to 10 mrad/hr as a function of shielding thickness. Table 6 gives the distance required to obtain this dose rate for standard tube housing and for 1, 2 and 3 TVL of concrete, steel, and lead.

A completely shielded enclosure 2-TVL thick will attenuate leakage to 10 mrad/hr (10 rad/week average) at a distance of 25 ft from the target. An unshielded source requires 10 times this distance (250 ft).

TABLE 6. DOSE RATE/DISTANCE REQUIREMENTS

Additional Shielding (TVL)	*Inches of Concrete*	*Inches of Fe*	*Inches of Pb*	*mrad/hr at 1m*	*10 mrad/hr m*	*at ft*
0	—	—	—	6×10^4	78.0	250
1	14.8	4.1	2.1	6×10^3	25.0	80
2	29.6	8.2	4.2	6×10^2	7.8	25
3	44.4	12.3	6.3	6×10^1	2.5	8

The permissible dose of radiation to personnel in an uncontrolled area is 10 mrad/week average with a maximum annual dose of 0.5 rads. For a work load of 50 hr/yr (1 hr/week) leakage radiation beyond 10m would be approximately of 10 mrad/week, making the region beyond this point an *uncontrolled* radiation area. This simple assumption neglects the effects of scattered radiation from the primary beam. However, shielding requirements for scattered radiation are less severe. This allows for considerably less overall shielding around the individual cells.

A TELS accelerator guide shielded to 0.001% is shown in Figure 14. The overall diameter of the guide and surrounding solenoids have been reduced to an absolute minimum. At the same time, the maximum diameter of the shielded assembly has been held to 12 in. as compared to 11 in. for the original guide with normal shielding. The diameter was kept to a minimum by using depleted uranium at critical locations, namely in the region of the target. Uranium has been used only at angles of 70 deg or greater with respect to the primary beam in order to eliminate the production of neutrons from the photofission process. This reaction occurs at X-ray energies greater than 5.5 MeV. At 70 deg there are essentially no neutrons produced above this energy. The forward part of the shielding enclosure is made of tungsten, a material with a density slightly less than that of uranium. The back part of the guide is shielding with lead, with a uranium cap used to intercept a narrow beam of backstreaming X-rays. The total weight of the shielding material is 1300 lb. With further optimization of the shielding geometry, it may be possible to reduce its overall weight to about 1,000 lb.

It is also possible to provide additional shielding for the LINATRON 3000. P&WA has designed a lead vault with walls approximately 4-in. thick to minimize leakage radiation. The weight of the lead vault is approximately 16T, which includes an allowance for a 6-in. free space around the accelerator structure. A somewhat smaller lead vault with 3-in. lead walls and a 4-in. free space is estimated to weigh approximately 10T. It becomes obvious that system weights for large X-ray sources become quite heavy because of the vault size required to contain the accelerator structure.

An alternate approach is to modify the LINATRON 3000 and add lead shielding directly to the tube housing similar to that of the TELS accelerator, Figure 14. An additional 4 in. of lead shielding added to the tube head would weigh approximately 6,000 lb. The overall dimensions of the LINATRON would increase from 66 by 28 by 29-in. to 80 by 40 by 40-in.

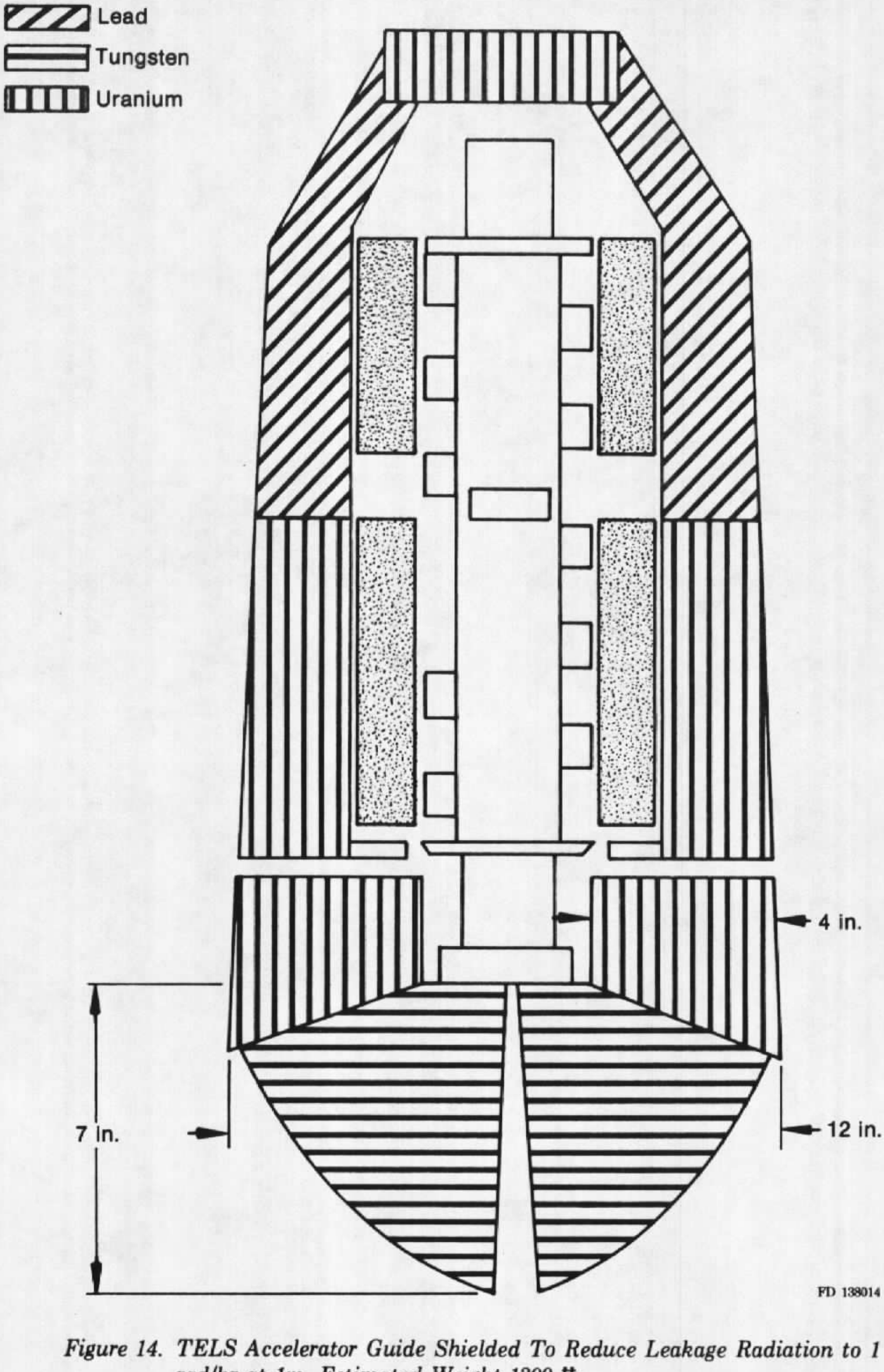


Figure 14. TELS Accelerator Guide Shielded To Reduce Leakage Radiation to 1 rad/hr at 1m, Estimated Weight 1300 lb

3.1.2 Shielding for Primary and Scattered Radiation

3.1.2.1 Primary Beam

The primary beam is emitted through a collimator with a cone angle of 8 deg. For a square field, the field size at 1m is 14 by 14 cm (~200 cm^2). The dose rate at 1m is 3,000 rad/min or 1.8×10^5 rad/hr. This is equivalent to an average workload of 1.8×10^6 rad/week.

The most efficient way to stop the primary beam is to point the beam vertically downward into earth and to restrict the beam travel to a minimum. Using earth as the primary barrier eliminates the need for a separate concrete (or lead) primary barrier. Unfortunately, this orientation is not possible for cells C-1/C-2 and J-2.

An alternative way of minimizing the size of primary beam barriers is by including a beamstopper or shielding dump directly behind the imaging system. The beamstopper should be thick enough to attenuate the primary beam to 0.1%, so that the escaping X-rays are comparable in intensity to leakage radiation. At these energies a lead beamstopper should have a minimum thickness of 6 in. and should be aligned to intercept the primary beam at any exposure geometry.

3.1.2.2 Scatter

Scattered radiation is the result of interactions of the test object or any material with the primary beam. Unlike primary and leakage radiation where beam parameters are well defined, shielding for a scattered radiation can only be approximated. The angular distribution and beam quality of 6 MeV X-rays scattered from a cylindrical object and from concrete slabs has been measured in earlier studies. All calculations were based on a 400 cm^2 beam size at 1m. Since our beam size is 200 cm^2 at 1m, the amount of scatter from our source will decrease by one-half. Table 7 gives the percent scatter as a function of beam angle and the TVL in concrete. For large angle scattering (greater than 90 deg) scattered radiation 1m from the scatterer will be approximately 0.03% of the primary beam at 1m. The TVL for 90-deg scatter in steel is 1.75 in. and decreases with larger angles. The first TVL for 90-deg scatter in lead is 0.34 in. decreasing to about 0.15 in. for 180-deg scatter. A modest amount of lead added to the existing steel walls would attenuate back-scattered radiation from the irradiated object to the same order of magnitude as leakage from the heavily shielded TELS source. Shielding for scattered radiation for angles greater than 90-deg presents no great problem.

Forward scattering around the beamstopper at angles from 30 to 90 deg presents one of the major shielding problems for cells C-1/C-2 and J-2.

TABLE 7. SCATTERED X-RAYS FOR 200-cm^2 FIELD AT 1m

Angle (deg)	*Percent Scatter at 1m*	*TVL for Concrete (in.)*	*IVL for Iron and Lead*
15	0.5	13.1	
30	0.2	10.5	
45	0.1	9.2	
60	0.05	8.0	
90	0.03	7.0	1.75 in. iron 0.34 in. lead
135	0.02	5.8	

3.2 Radiation Safety

The information provided in this section constitutes excerpts from NBS Handbook 107[8]. This handbook applies to radiation safety in the design and operation of particle accelerators. It considers the characteristics of and controls for radiation safety as they affect accelerator design, operating procedures, and exposure evaluation. NCRP Report No. 51[9] was also helpful.

3.2.1 Radiation Shielding Considerations

The purpose of providing radiation shielding around a particle accelerator installation is to ensure that *all* radiations within the radiation enclosure are attenuated to levels such that the maximum permissible dose is not exceeded (1) for radiation workers, in controlled areas, or (2) for the general public, in uncontrolled areas. Radiation attenuation can be accomplished by a reasonable combination of (1) distance from the sources of radiation and (2) physical shielding barriers.

An expert should be consulted in the design of a particular accelerator installation and called upon to perform a radiation survey when the accelerator is first ready to produce radiation. The accelerator designer should provide all possible information concerning the sources of primary and secondary radiations from the specific accelerator under consideration. In the absence of sufficient information, the accelerator facility designer should assume that the radiation characteristics are the same as for equivalent or larger accelerators operating according to the same principle of operation.

The shielding design should be based on the maximum radiation output of the accelerator. The possibility of operating later at higher energies and/or intensities should be anticipated in the original facility design, within reasonable extrapolations of the expected performance.

The shielding design should also conform to all applicable federal and state regulations pertaining to the specific accelerator installation under consideration, its intended use, and its ancillary apparatus and materials.

3.2.2 Safety Systems

The purpose of this section is not to design or specify safety systems required in various circumstances, but to indicate methods by which the required protection may be achieved. The recommendations are not intended to preclude alternative methods of achieving the radiation protection objectives. They may be modified upon the advice of an expert.

The objective of a safety system is to prevent injury or damage by radiation, and its success depends inevitably on the understanding and control of the people who will be associated with it. Materials and workmanship utilized in the design and installation of the safety system should be of the highest grades for dependability and long life. Fully enclosed components should be used wherever practicable, and methods of actuation should be as failureproof and tamperproof as possible. The principle of a fail-safe should apply whenever practicable in the design and execution of safety systems. Duplication of methods or redundancy of devices should be considered when it would seem that dependability can be justifiably enhanced.

Maximum reliance should be placed on passive rather than active elements of a safety system. Where possible, wall barriers and locks should be relied upon as compared with warning lights, bells, radiation detection devices, or electrical surveillance systems.

3.2.3 Accelerator Controls and Interlock Systems

Primary controls governing the production of radiation shall be capable of being secured (locked) to prevent unauthorized use. Provisions shall be made in radiation control circuits for the safety interlocks and warning systems. These provisions should not be dependent upon the operation of a single circuit and should be designed so the specific interlock triggering an alarm condition is readily identifiable.

All entrances into an accelerator room or exclusion area shall be provided with interlock systems. A scram switch, pull-chain, or other emergency power cutoff switch, shall be located within easy reach, and be easily identifiable, in exclusion areas. Such a cutoff switch shall have positive indication as to the operative position of the switch, and shall include, at the same location, a manual reset, so that the accelerator cannot be restarted from the accelerator control console without manually resetting the cutoff switch.

3.2.4 *Warning Devices*

All locations designated as high radiation areas, and entrances to such locations, shall be equipped with easily observable flashing or rotating purple warning lights that operate automatically when, and only when, radiation is being produced. Lights of a different color shall be used for other visual indicators when they are required. Redundancy shall be built into the system such that an alarm will sound in the event radiation is produced and the warning light has malfunctioned.

In a large facility, audible warnings shall be given prior to startup of the accelerator. Horns or buzzers should be located in areas with readily accessible scram switches. There shall be no possibility of confusion between the tone and characteristics of these audible systems and the Immediate Evacuation Signal. The audible warning should have a duration such that a person's attention would be attracted above ambient noise, and that he would have time to reach a scram switch or to safely evacuate the space.

Continuous radiation-monitoring devices should be operating in or adjacent to high radiation areas, or in other areas where radiation intensity may increase with the operational level of the accelerator. Such monitoring devices shall provide an audible warning to personnel in the vicinity when preset levels are exceeded. All safety and warning devices including interlocks shall be serviced and checked for proper functioning at intervals not to exceed 6 months.

3.3 Operational Health Physics

3.3.1 *General Considerations*

The responsibility for the protection of the worker and environment in its broadest sense rests with management. A radiation safety program shall be developed in accordance with federal and state regulations.

ANSI standards and recommendations of authoritative bodies such as the Federal Radiation Council (FRC), The National Council on Radiation Protection and Measurements (NCRP), and the International Commission on Radiological Protection (ICRP) should be considered, as appropriate, in the development of a radiation safety program.

3.3.2 Radiation Safety Organization and Responsibility

When implementing a radiation protection program, management shall appoint a radiation control officer and, if appropriate, a radiation safety committee. The qualifications of the radiation control officer should be determined by the technical requirements dictated by the work as well as the complexity and size of the operations, and shall include a basic understanding of radiation protection principles. As a minimum requirement, the services of an expert shall be obtained during the early planning stages or engineering phase of any new accelerator.

The radiation control officer shall develop and promulgate an effective radiation protection program, consistent with appropriate federal, state, and local regulations. He shall advise management and accelerator operators on all matters pertaining to radiation safety. The accelerator operator shall be responsible for all operations connected with the accelerator, including radiation safety. The radiation control officer shall have the authority to cease operations when necessitated by radiation safety considerations.

3.3.3 Radiation Safety Procedures

Written operating and emergency procedures pertaining to radiation safety shall be developed and reviewed periodically by an expert or radiation control officer for each accelerator facility and approved by the accelerator operator and management. Operators and other appropriate personnel shall be familiar with and be given a copy of the written operating and emergency procedures pertaining to radiation safety. In addition, such procedures should be posted near the accelerator control console and other areas as appropriate.

Operators and other appropriate personnel shall be responsible for: (1) keeping occupational exposure to radiation as low as practicable, (2) wearing personal radiation dosimeters in the prescribed manner, (3) following radiation safety rules and regulations, (4) reporting radiation accidents, incidents, and unsafe working conditions, and (5) keeping a written log of interlock shutdowns or other indications of hazardous radiation conditions.

3.3.4 Personnel Monitoring Requirements

The radiation control officer or his designated alternate shall supply appropriate personnel-monitoring devices and shall require the use of such devices by:

- Each individual who is likely to receive a dose equivalent (DE) in any calendar quarter in excess of 25% of the maximum permissible dose.

- Each individual under 18 years of age who is likely to receive a DE in any calendar quarter in excess of 60 mRem.

- Each individual who enters a high radiation area.

Appropriate personnel-monitoring devices are designed to be worn or carried by an individual for the purpose of measuring the DE. Examples of such devices are film badges, pocket ionization chambers, thermoluminescent dosimeters, chemical dosimeters, activation foils, photoluminescent devices, fission track records, etc.

3.3.5 *Area Monitoring Requirements*

Before a new installation is placed in routine operation, a radiation protection survey shall be made by an expert. A radiation protection survey shall be performed and documented when changes have been made in shielding, operation, equipment, or occupancy of adjacent areas, and periodically, to check for unknown changes and malfunctioning equipment.

Radiation levels in all high radiation areas should be continuously monitored. The monitoring devices shall be capable of providing a remote and local readout with visual and audible alarms at both the control panel and monitoring locations. The monitoring device should be equipped with a bright purple rotating light visible to any personnel entering the area.

3.3.6 *Interlock and Warning Systems*

Particle accelerators shall be secured when not in operation to prevent unauthorized use. A continuous radiation-monitoring system shall be operational and located in proximity to the accelerators with associated readout and preset alarm devices located within the machine area, and at the control console. A control switch on the accelerator control console shall be used to turn the accelerator beam on and off. The safety interlock system shall not be used to turn off the accelerator beam except in an emergency. If the interlock system turns off the accelerator, it shall not be possible to resume operation without resetting the accelerator "On" switch at the control console. All safety and warning devices, including interlocks, shall be checked for proper operability at intervals not to exceed 6 months.

If, for any reason, it is necessary to intentionally bypass a safety interlock or interlocks, such action shall be: (1) authorized by the accelerator operator and radiation control officer on each shift, (2) recorded in a maintenance log or other record and posted at the accelerator control console, and (3) terminated as soon as possible.

3.3.7 *Education and Training*

Operating personnel shall: (1) receive appropriate radiation safety training, and (2) demonstrate competence to use the accelerator, related equipment, and radiation survey instruments. Training should include but not be limited to the following:

1. Fundamentals of Radiation Safety

   - Characteristics of particulate and electromagnetic radiation
   - Units of radiation dose and quantity of radioactivity
   - Biological hazards of exposure to radiation
   - Measurement of radiation
   - Methods of controlling radiation dose
   - Radiation safety procedure, interlock systems, and warning systems.

2. Fundamentals of Radiation Detection

   - Use of radiation survey instruments
   - Survey techniques
   - Use of personnel-monitoring equipment.

3. Equipment

   - Operation and control of accelerator equipment
   - Remote handling equipment
   - Handling of activated materials
   - Use of shielding.

3.4 Test Cell Shielding Design Studies

3.4.1 Test Cell J-5

Test cell J-5 is a horizontally oriented test cell designed primarily for static testing of large solid-propellant rockets. The test area is a cylindrical section 16 ft in diameter and 50-ft long. A 10- by 30-ft loading hatch at the top of the capsule provides access into the cell.

The J-4/J-5 test area is isolated from the other test facilities. Figure 15 shows the area and the earth barricades surrounding test cell J-5. These barriers provide essentially complete protection from direct leakage radiation except in the north direction towards test cell J-4. An additional earth barricade protects the J-4/J-5 control room complex located approximately 600-ft northeast of the J-5 test cell.

The Varian LINATRON 6000 X-ray accelerator has been recommended as the source for test cell J-5 applications. The 15 MeV X-ray spectrum provides maximum penetration through the massive solid propellant rocket motors. The X-ray output is more than adequate to allow the LINATRON 6000 to be mounted externally. Figure 16 shows schematically the LINATRON 6000 positioning system proposed for test cell J-5. This is the most practical source-mounting arrangement since it allows a 5-ft thick concrete reactant wall, located on the east side of the cell, to intercept the primary beam. The height of the concrete wall is about 2-ft less than the height of the test cell and extends well beyond the lateral travel of the X-ray source. Five feet of concrete will attenuate the primary beam (TVL=17 in.) by 3.5 TVL making it comparable to leakage radiation.Additional shielding is required at the location of the 48-in. diameter hole for the ejector duct in the reactant wall. This primary shield will eliminate the need for a lead primary beamstopper behind the X-ray detector and real-time imaging system. However, it will be necessary to limit the vertical rotation to ensure that the primary beam intercepts the reactant wall under all exposure conditions.

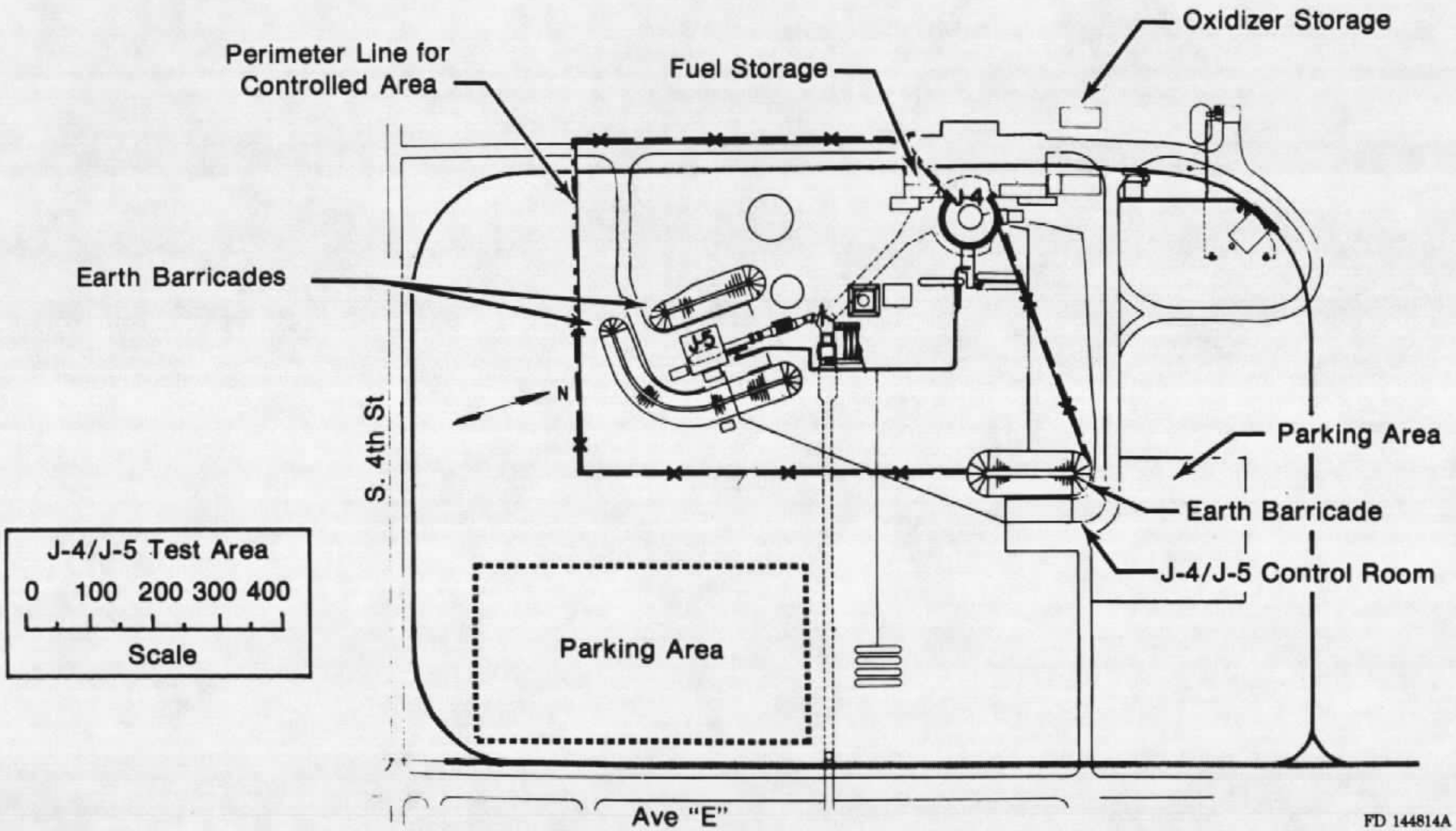


Figure 15. Plan for the J-4/J-5 Test Cells

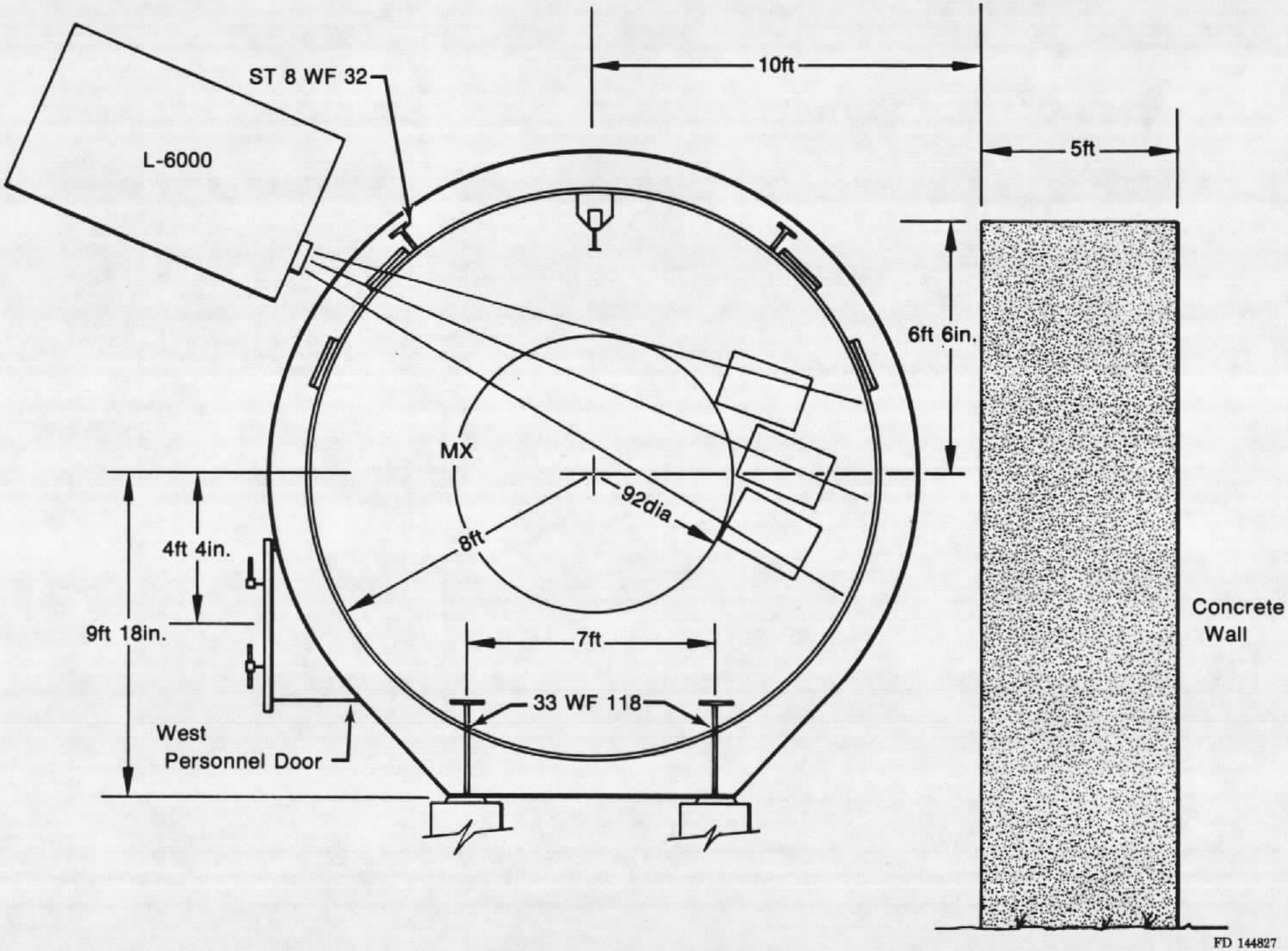


Figure 16. LINATRON® 6000 Proposed for the J-5 Test Cell

For the LINATRON 6000, in test cell J-5, assume:

1. Primary X-ray dose rate, 6000 rad/min at 1m

2. Leakage, 0.001 of the primary beam

3. TVL, 17-in. concrete, 4.4-in. steel, 2.1-in. lead

4. Work load, 1 hr/week or 50 hr/year and 3.6×10^{5} rad/week at 1m

5. X-ray window, 3-in. thick aluminum in cell wall

6. Attenuation of X-rays in 60-in. concrete wall, 3.2×10^{-4}

7. Uncontrolled area, 10 mrad/week or 10 mrad/hr for a use factor of 1 hr/week

8. Distance for 10 mrad/week perimeter (leakage):

   For air density of 0.0013 g/cm^3 = 160m or 525 ft

9. Skyshine at 100 ft for ψ = 15 deg, 8 mrad/hr and for ψ = 5 deg, 12 mrad/hr (See figure B-4, Appendix B[10].)

10. The 5-ft thick concrete reactant wall completely stops the primary beam

11. The earth barricades are sufficiently high so that the angle ψ defined by the target and the shield (figure B-4) is no less than 5 deg and preferably greater.

With the area evacuated, there is no problem of scattered radiation. As a result, there is no need to shield the 12-in. diameter access ports located throughout the cell.

The J-4/J-5 test cells are completely evacuated during testing. This condition considerably simplifies the shielding requirements. Leakage radiation projecting over the earth barricades will result in skyshine radiation projected towards ground, which decreases inversely with distance. Figure B-2 gives skyshine dose rates at 20 ft as a function of angle defined by the source and the shield. For ψ = 5 deg the skyshine dose rate at 20 ft for the LINATRON 6000 is approximately 60 mrad/hr. At a distance of 100 ft, the dose rate will decrease by a factor of 5 to approximately 12 mrad/hr. With the center of the earth barrier 100 ft from the target, ψ = 5 deg would require the top of the earth mound to be 8.7 ft above the X-ray target. In order to attenuate leakage radiation to 10 mrad/hr, the earth barrier must be 60-in. thick.

Open areas not shielded by the earth barrier require a perimeter line determined by inverse square. The 10 mrad/hr (10 mrad/week) line will be at a distance of 525 ft from the X-ray target. The controlled area perimeter line is shown in figure 15.

It should be noted that accelerators employing heavy metal shielding, such as lead and tungsten, will produce leakage neutrons due to photodisintegration processes when operating above approximately 8 MeV. Machines operating at energies above 10 MeV will have difficulty in meeting currently accepted leakage specifications which include neutron rem dose levels. Photoneutron production becomes a serious problem for X-ray accelerators operating at 15 MeV. At this point, neutron leakage on a rem basis becomes equivalent to that from X-rays. For this reason, an additional 4 to 6 in. of polyethylene has been added as neutron shielding in the LINATRON 6000 in order to reduce neutron leakage to manageable levels, particularly from skyshine. Neutron leakage and skyshine measurements made on three operating LINATRON 6000s indicate that the problem has been minimized.

3.4.2 Shielding Requirements for Test Cell J-2

The shielding equations from NCRP Report No. 49[11] and the following assumptions were used in determining barrier requirements for J-2.

General Assumptions:

1. The TELS Source (3000 rad/min at 1m) with added shielding is located within cell J-2 with the primary beam pointing south into an outside wall.

2. Added shielding reduces leakage radiation at 1m to 0.001% of the primary beam at 1m.

3. Maximum X-ray energy is 8 MeV.

4. Tenth valve layer (TVL) of the primary beam is 14.6-in. concrete, 4.15-in. iron and 2.2-in. lead.

5. Accelerator is to be installed inside the test cell pointed horizontally.

6. Primary beam is collimated to 8 deg or less.

7. Horizontal beam travel is 100 in.

8. Horizontal beam tilts ±30 deg about the horizontal axis.

9. Beamstopper behind the imaging system is about 3-TVL thick, equivalent to 6.5 in. of lead.

10. The workload is 1 hr/week or 50 hr/year, which is equivalent to 1.8×10^{6} rad/week at 1m. The leakage workload through 2-in. steel cell is 6×10^{4} rad/week at 1m.

11. The closest work station to be occupied by personnel is the J-1 control room located about 80 ft from the source. The J-1 control room shall be an uncontrolled area, with restricted access during beam-on.

12. Barrier thickness calculations shall be based on an average exposure rate of 10 mrad/week as specified for an uncontrolled area.

13. All access ports which allow scatter radiation to leak back into the J-2 room at levels where the maximum permissible dose rate is exceeded must be properly shielded.

3.4.2.1 Concrete Wall Outside of Cell J-1/J-2 Building

This wall is required in order to provide a defined perimeter to ensure that the T-3 Test Building and the adjoining region remains an uncontrolled area. The central region of this wall is where the primary beam (attenuated to 0.1% by a beamstopper) will impinge. There is an access road directly outside the building. A concrete counterweight for the door hatch travels up and down just outside the wall; consequently, the shielding barrier cannot be constructed as a part of the outside wall, which would be the most desirable location. It may be possible to relocate the counterweight outside such a concrete wall. At present, the only possible location is 52 ft from the central axis, just beyond a graded trench running parallel to the south wall. The centerline of cell J-2 is 18 ft above ground. The X-ray accelerator is positioned horizontally at this height. For D = 55 ft and W = 6×10^{4} rad/hr, the wall thickness required to reduce the primary beam to 10 mrad/ hr is 20 in. of concrete while 30 in. will be required to reduce instantaneous dose rate to 2 mrad/hr. Since the cost of extra thickness of concrete is small compared to the cost of preparatory work (framing, reinforced steel rods, etc.), a 30-in. wall is, therefore, recommended for the area intercepted by the primary beam.

In order to obtain complete radiographic coverage of a turbine engine, the X-ray beam is designed to swing through an arc of ±30 deg. It is impractical to build a wall high enough to intercept the beam pointing 30 deg upward. A more practical approach is to limit the wall height

to 35 ft to cover a vertical angle of 15 deg, and add lead to the outer cell wall as required to provide shielding for the remaining 15 deg arc.

Skyshine from a 35-ft high wall (ψ = 15 deg) may be estimated from figure B-4 for the LINATRON 2000. Figure B-1 is for an isotropic distribution of radiation from a point source. In our case, we are limited to an 8-deg cone angle, plus some scatter radiation. This indicates that the number obtained will be too conservative, possibly by as much as a factor of ten. The skyshine dose rate for a distance of 20 ft is 36 mrad/hr and decreases linearly with distance. At 60 ft the dose rate is 9 mrad/hr. One inch of lead (~1 TVL) on the outer surface of cell J-2 over the surface swept by a 15- to 30-deg beam with a horizontal travel of 100 in. covers an area of about 22 ft^2. This amounts to 700 lb of lead to reduce skyshine to 2 mrad/hr.

One can also apply a use factor of 25% for the time the beam will be positioned between 15 to 30 deg in the up direction. This consideration reduces the skyshine dose at 60 ft to 2 mrad/hr without the requirements of additional lead shielding.

Table 8 gives the scattered radiation of 15-30-45-60-90-135 and 180 deg. Percent scatter and the TVL in iron were obtained from table 7 using the concrete equivalence of iron. Column 5 gives the slant thickness through the 2-in. steel cell wall vs angle. In such a calculation, the distance becomes infinite for 90 deg. Column 6 gives the rad/hr at an arbitrary distance of 10m or 33 ft. Column 7 gives the rad/hr at a slant thickness of 17m, or 55 ft, the source to wall distance for the primary beam. Beyond 60 deg the contribution from scattered radiation becomes negligible.

TABLE 8. DOSE RATE FROM SCATTERED RADIATION AT 55 FT AFTER PENETRATING 2-IN. STEEL WALLS OF TEST CELL J-2

Scatter Angle (deg)	*Percent Scatter**	*rad/hr at 1m*	*TVL Iron (in.)***	*Effective Cell Thickness (in.)*	*mrad/hr 10m*	*mrad/hr 17m (55 ft)*
15	0.5	900	3.75	2.07	2,570.0	870
30	0.2	360	3.3	2.31	720.0	250
45	0.1	180	3.0	2.83	205.0	70
60	0.05	90	2.5	4.00	22.5	10
90	0.03	54	1.8	∞	—	—
135	0.02	36	1.5	2.83	4.0	—
180	0.02	36	1.2	2.00	8.0	—

* Percent scatter taken from table 7.

** Obtained from the concrete equivalence of iron in NCRP Report 49[11]. Percent scatter for 6 MeV X-rays has been used under the assumption that the higher energy will decrease scatter rather than increase it. For angles greater than 45 deg, the TVL of scatter radiation is relatively insensitive to energy. Comparisons of the TVL in concrete for 6 MeV X-rays and Co-60 gamma rays show only minor differences at the larger angles. (See tables 18 and 21 in Reference 10.)

The concrete barrier is shown in figure 17. It extends over the entire building length, is 30-in. thick in the central region and is 20-in. thick over the remaining region; the wall is 35-ft high. There are two additional concrete shields at each corner of the building 12-in. thick and 25-ft high. They are intended to cover scatter angles up to 60 deg. The remaining region is zoned off as required to provide a 10 mrad/week perimeter, which is readily achievable.

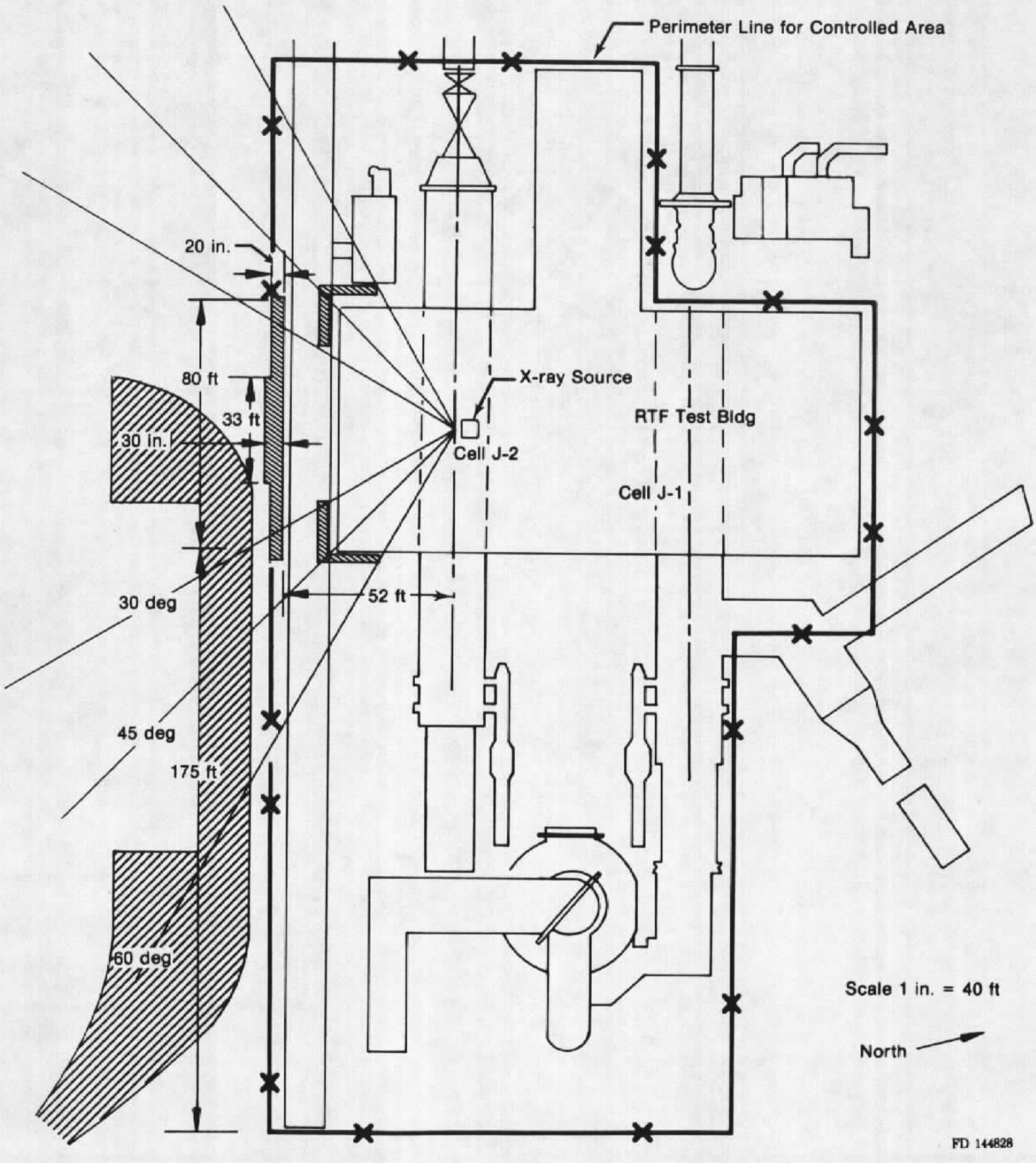


Figure 17. Concrete Barrier and Perimeter Shield for the J-2 Test Cell

3.4.2.2 Scattered Radiation in the J-1/J-2 Room

Since scatter radiation in the room will be at angles greater than 90 deg, the data from table 8 for 135 and 180 deg at 10m can be used as an index of hazard.

The largest value obtained was 8 mrad/hr at 180 deg. It is concluded that there is no scattering problem with the accelerator mounted in the test cell.

Some modifications will be required. Access ports from which scattered radiation could cause excessive leakage at J-1 (if occupied) must be properly shielded. The shielding equivalence would be 2 in. of steel.

There is no hazard to the control area when X-ray head leakage is reduced to $10^{-5} \times$ the primary beam.

3.4.3 Shielding Requirements for Test Cells C-1/C-2

The same assumptions were used in determining barrier requirements for C-1/C-2 as for J-2, with the following modifications:

1. The LINATRON 3000 source (3000 rad/min at 1m) with added shielding is located within both cells C-1 and C-2. Note that the TELS source could be substituted for the LINATRON 3000 with essentially the same end results.

3. The maximum X-ray energy is 10 MeV. Photoneutrons are produced at this energy. Neutron leakage at 1m is about 0.03% of the primary X-ray beam.

4. The TVL of the primary beam is 15.3-in. concrete, 4.2-in. iron and 2.2-in. lead.

5. The accelerators are to be installed inside the test cells with the X-ray beam pointed horizontally.

11. The closest station to be occupied by personnel is the Data Conditioning Room, located on the second floor 25 ft behind the source for both cells C-1 and C-2. This room will be designated a radiation controlled area. The C-1/C-2 control room shall be an uncontrolled area.

12. The centerline of cells C-1/C-2 are approximately 12 ft above ground.

3.4.3.1 Concrete Wall Outside of Cell C-1/C-2 Building

Because of space limitations this wall must be located approximately 80 ft from central axis of both cells (figure 18). Since the cells are mirror images, only one analysis will be made. For D = 80 ft and W = 6×10^4 rad/hr, the wall thickness required to reduce the primary beam to 10 mrad/hr is 16-in. concrete and to 2 mrad/hr is 26-in. concrete. A 26-in. thick wall is recommended. The primary barrier is 55 ft wide, while the overall length of the concrete wall is 150 ft. The wall is 30 ft high and tapers from 26 in. at the edge of the 55-ft wide barrier to 10 in. at both sides. The concrete barrier intercepts scattered radiation through at least 45 deg. The perimeter line extends 25 ft beyond the end of each wall on both sides. The perimeter line shown in figure 18 reduces radiation levels outside the building to below 10 mrad/week.

3.4.3.2 Scatter Radiation in the C-1/C-2 Room

Leakage for 135- and 180-deg scattered radiation at 10m will be 4 and 8 mrad/hr respectively. The first level mechanical work room should be completely evacuated and secured during operation of the X-ray accelerator. The Data Conditioning Room appears to have 6-in. concrete walls on either side of cells C-1 and C-2. This amount of shielding will reduce scattered radiation by an additional tenth value layer. However, leakage radiation at the inside surface of these walls will be approximately 10 mrad/hr. It is recommended that the Data Conditioning Room be designated as a radiation area and be controlled accordingly. None of the other rooms in the building are expected to receive dose rates in excess of 2 mrad/hr.

3.4.4 Neutron Leakage

The one concern with a shielded LINATRON 3000 in cell C-1/C-2 is a potential neutron shielding problem. For 10 MeV X-rays neutron leakage is somewhere 0.01 to 0.03% of the primary X-ray leakage. These neutrons will readily penetrate steel and lead. With no additional shielding neutron dose rates as high as 500 mrem/hr at 10m can be expected. No provisions have been made for neutron shielding other than that provided by concrete walls. Concrete is an effective neutron absorber with a TVL of about 10 in. Neutrons are most readily shielded with hydrogenous material such as polyethylene. Partial shielding of the collimator and the forward portion of the accelerator with about 2 in. of polyethylene will minimize neutron leakage. The problem will be investigated further as required.

Since the threshold for photoneutron production is about 8 MeV, the TELS source operating at this maximum X-ray energy does not present a neutron leakage problem.

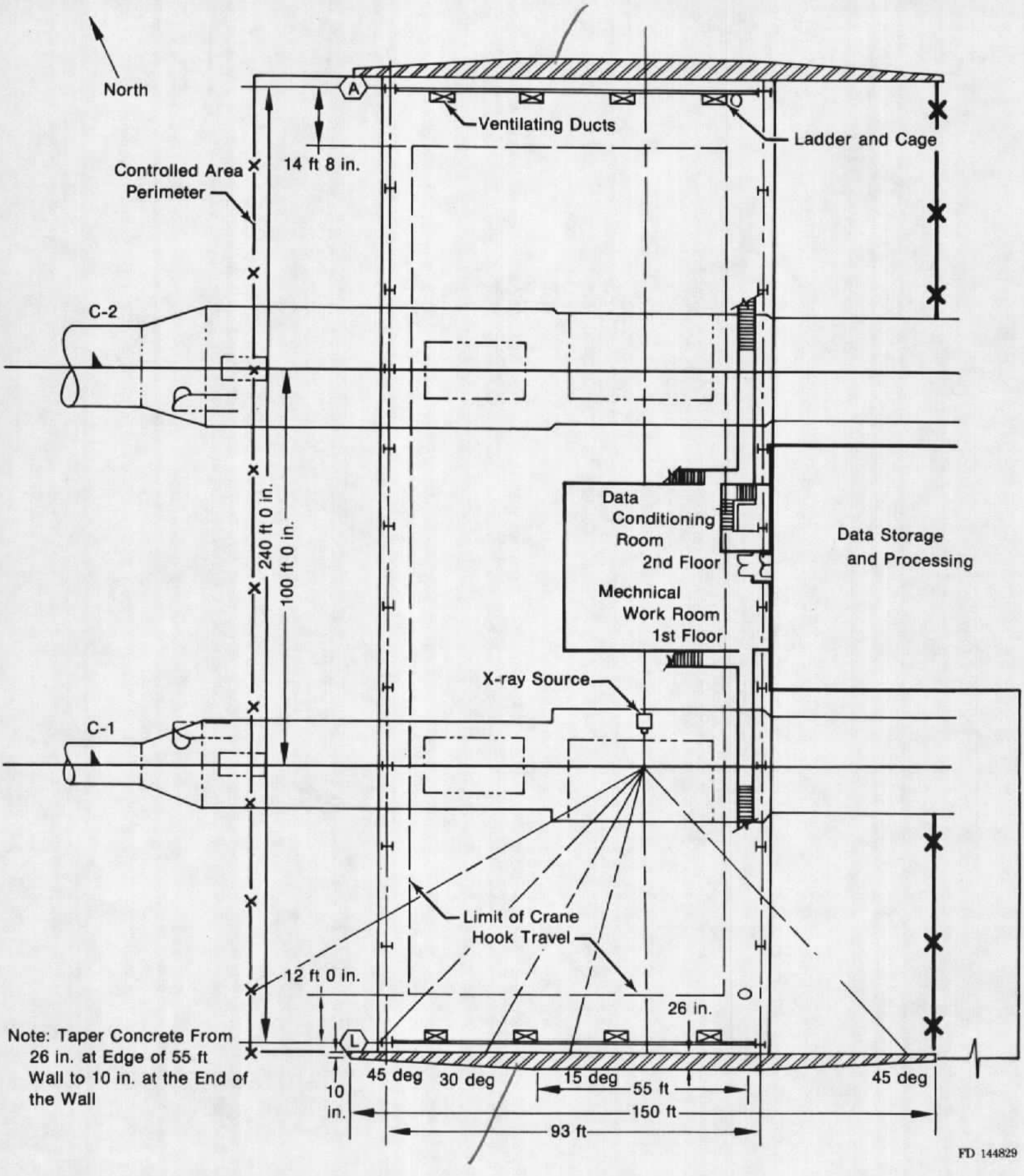


Figure 18. Plan of Facility With Concrete Barrier and Perimeter for Test Cells C-1/C-2

SECTION 4
IMAGING SYSTEM (LMSC)

4.0 TASK REQUIREMENTS AND DESIGN CONCEPTS

4.1 Engine Radiography Requirements

4.1.1 Turbine Engines

The primary task in turbine engine radiography is to obtain measurements of internal clearances, axial and radial, under various conditions of engine operation in the specified test cells.

4.1.2 Rocket Engines

The following are areas of interest in static test firing of rocket engines:

- Measurement of the nozzle throat diameter
- Determination of the burn pattern
- Measurement of flame-front propagation rates
- Detection of grain distortion, structural deformation
- Examination of high stress areas such as the base of the wing slots
- Measurement of the gap between the forward dome and the insulator (flap gap)
- Measurement of insulator ablation rates
- Measurement of nozzle erosion rates.

4.2 Design Requirements

4.2.1 Detector

The following requirements have been established for the design of the detector in general:

- Suitable for high-energy, X-ray radiography of both turbine engines and rocket engines under altitude test conditions.

- Consist of a combination film-changer and electronic imaging system with concentric fields of view. The requirement for a combination detector is based primarily on the need for the presently superior quality of film images and the need for precise source alignment for axial clearance measurements in turbine engines, which is satisfied by the electronic imaging system

- Compatible in design and operation with the TELS detector

- Designed for minimum transmission of external noise and vibration to internal components

- Incorporate internal shielding against backscattered radiation. This requirement is necessary for proper operation of the electronic imaging section

- Portable so that one detector can be used for all test cells

- Designed for convenient maintenance and repair

- Include in design protection from the thermal radiation from rocket and turbine engine exhaust plumes

- Design consideration protection from damage due to overpressurization and flying objects.

Particular design requirements on the film-changer section of the detector are:

- Provide a change rate of 1/sec. This requirement is based on requirements for turbine engine radiography discussed in the TELS Radiographic System Study[1], and is also suitable for rocket-engine radiography

- Provide a field of view of 14 by 24 in. The development of this requirement is discussed in paragraph 4.4.1

- Provide for changing intensifying screen types. This allows the needed capability to trade-off between image quality and time resolution

- Use 14-in. wide roll film. This provides suitable coverage for turbine-engine and rocket-engine radiography and compatability with the TELS system

- Allow convenient film change.

The electronic imaging section of the detector should provide a 12 by 12 in. field of view. This requirement is discussed in paragraph 4.4.1. It should also operate properly in the test-cell noise and vibration environment.

4.2.2 Control System

The control system should provide the following capabilities:

1. Manual control capability

2. On-line computer control capability for system check-out, system diagnostics, and test program execution including source and detector repositioning during test

3. Accept the following sensor inputs:

   - Turbine revolutions per minute (rpm)
   - Turbine temperature — multiple inputs
   - Turbine rotor angular position
   - Position encoder outputs
   - Radiation dose rate (3 channels)
   - Integrated radiation dose

4. Provide for console generation of the test program

5. Provide for piecewise automatic or fully automatic modes for test execution.

4.3 Performance Requirements

The following performance requirements are based on Lockheed Missile and Space Company (LMSC) assessment of the present state of the art. The best possible spatial resolution will be required in order to approach the desired accuracy of ± 0.025 mm[1] for turbine-engine internal clearance measurements. Adequate measurement of the nozzle throat diameter of rocket engines will be equally demanding on spatial resolution requirements.

4.3.1 Film Radiography

The film-changer part of the imaging system should be capable of achieving the following sensitivity levels:

- With a 3.5-in. thick steel test object and a linac source of 8-10 MeV X-ray radiation having a focal spot diameter of 1 mm or less, a sensitivity level of 1 - 2T.

- Through 92 in. of propellant with a linac source of 12-15 MeV X-ray radiation having a focal spot size of 1 mm or less, a sensitivity level of 1 - 2T.

4.3.2 Electronic Imaging

The electronic imaging part of the system should be capable of achieving the following sensitivity levels:

- With a 3.5-in. thick steel test object and a linac source of 8 to 10 MeV X-ray radiation having a spot size of 1 mm or less and dose rate of 3000 rads/min or more at 1m, a sensitivity level of 2 - 2T in real time.

- Through 60 in. of propellant with a linac source of 12 to 15 MeV radiation having a focal spot size of 1 mm or less and a dose rate of at least 6000 rads/min at 1m, a sensitivity level of 2 - 2T with image integration.

4.4 Imaging System Conceptual Design

4.4.1 Detector

Two detector designs are submitted: (1) a primary detector suitable for J-2, C-1/C-2, J-5, and (2) an optional detector array for J-5 which is discussed in the following paragraphs. The primary detector conceptual design has been based on the TELS detector conceptual design[1]. The image size specified for the TELS detector is 14 by 14 in. for the film changer and 6 by 6 in. for electronic imaging. These specifications provide adequate field of view and allow a compact detector package as required for TELS. The requirement for the altitude cells under this study is somewhat different.

One important function of the detector for radiography in the test cells will be to measure the diameter of the MX nozzle throat during test firing. The diameter of the 2nd-stage MX nozzle throat will be about 11.5 in. It will be necessary to obtain an image delineating both sides of the nozzle throat in order t measure the throat diameter. This image should span at least 15 in. at

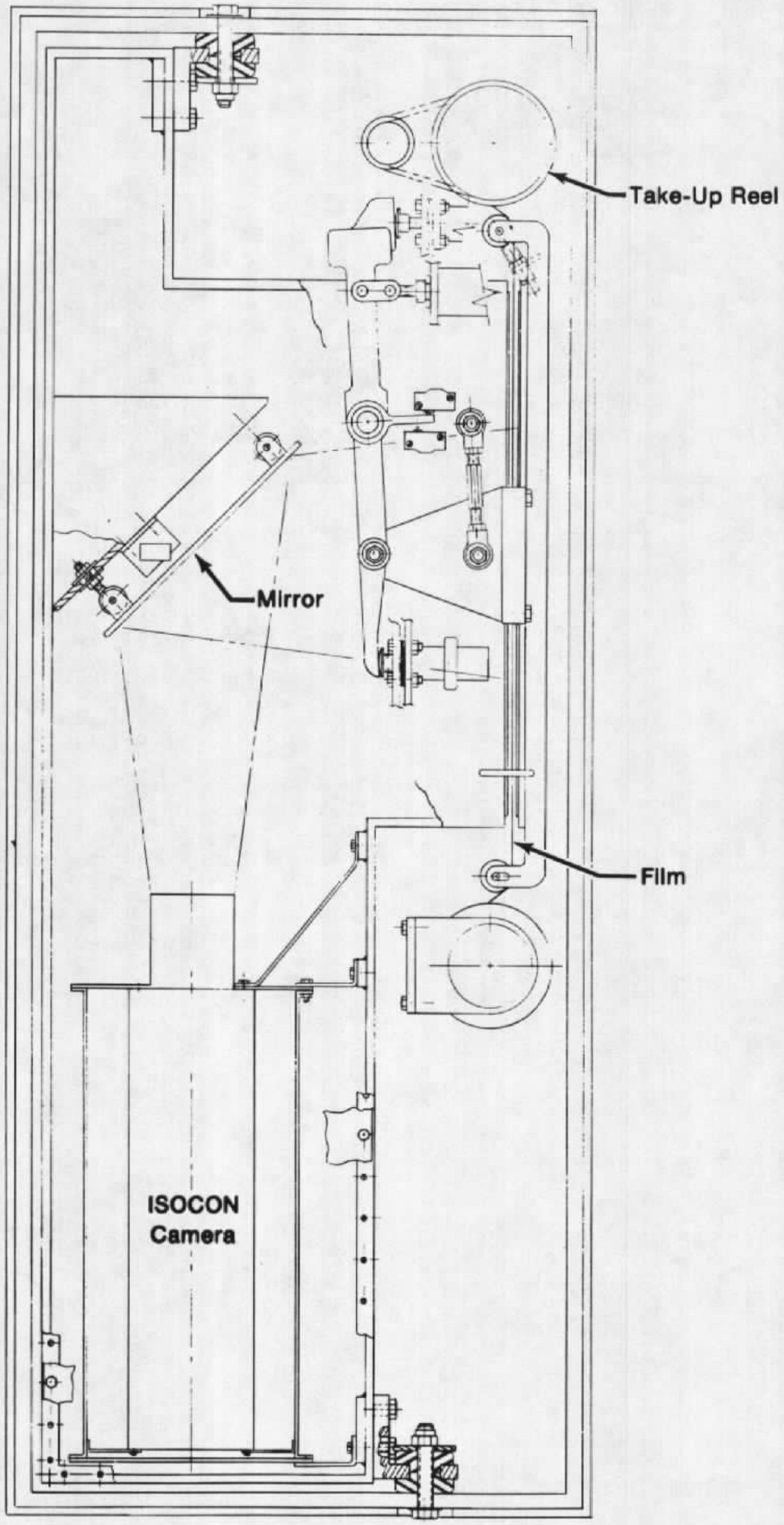
the nozzle. Considering that at the film plane the nozzle image is about one third larger than actual size, the width of the magnified image of interest is then about 20 in. Allowing ± 2 in. for alignment uncertainty gives 24 in. for the required length of the film image.

The image size for the electronic imaging section has also been increased over that of the TELS design. The reason for this is that a significant increase in the field of view can be obtained without significant loss in spatial resolution. Spatial resolution is limited by inherent unsharpness which for 8 MeV radiation is on the order of 0.6 mm. This value of 0.6 mm will limit the resolution to about 3 television monitoring lines per millimeter at the screen. The field size should be chosen so that as large an area as possible can be viewed without reducing the ability to resolve detail significantly below that limit imposed by inherent unsharpness. For an isocon camera capable of a limiting resolution of 1000 TV lines, and a 12-in. wide field of view, the resolution limit at the screen as imposed by the camera will be on the order of 3.3 TV lines per millimeter, which satisfies the above requirement. A 12 by 12 in. image size has been chosen. This image size will, for example, give a 9- by 9-in. field of view on the centerline of an MX motor with a source to film detector distance (SFD) of 200 in. and a motor-centerline-to-detector distance of 50 in.

Figure 19 shows the conceptual design of the detector. The filmchanger design incorporates an air-driven, statically-balanced, parallel-arm linkage with shock absorbers for screen actuation, an air-motor driven, drag-brake restrained, film advance mechanism, and chambers with slight (0.1 psi) positive air pressure to ensure intimate screen-film contact.

The electronic imaging section consists of a metal/phosphor screen obtained by phosphor coating the back screen of the film changer, a low-light-level TV camera in a separate, air-cooled, hermetically-sealed enclosure, and a mirror to fold the optical path so that the X-ray beam does not strike the TV camera. These components are attached to a subchassis which is mounted to the outer housing with four shock mounts. The space between the subchassis and the outer chamber is evacuated for improved noise isolation.

A detector for automatic exposure control is placed behind the mirror for electronic imaging. This detector consists of an internally-packaged, calcium fluoride scintillator and gallium arsenide phosphide photodiode. These aspects of the design are the same as TELS except that whereas the TELS detector uses a doubly-folded optical path to make the detector more compact, this detector uses a singly folded path to better accommodate the larger field of view.



FD 144830

Figure 19. Detector Concept Design

The TV camera is an isocon in a hermetically-sealed container, which may be hard-mounted or soft-mounted to the subchassis. This choice of mounting will be made on the basis of image quality determined empirically in the operational environment. The isocon tube *cannot* be tilted faceplate down at any time, regardless of whether or not the tube is being operated, without danger of photocathode damage by loose particles in the tube. Interlocking, therefore, must be provided to ensure that the detector is never positioned with the isocon tilted faceplate down.

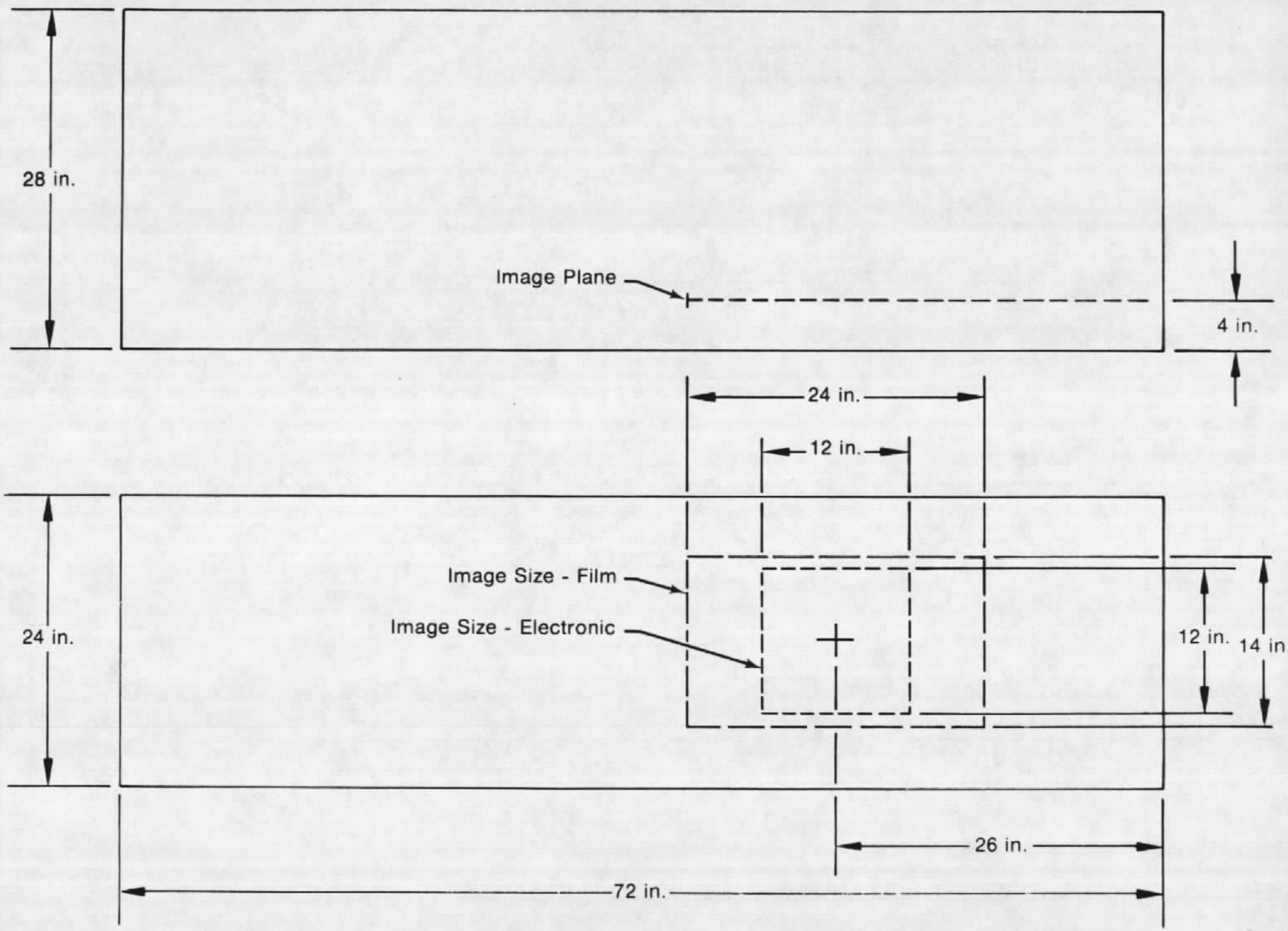
An illuminated test pattern, for use in adjustment and check-out of the isocon TV camera, will be included in the detector design. This pattern will be made viewable by swinging the mirror out of the camera field of view.

The inside walls of the detector, where visible from the screen, are lined with a 3/16-in. lead sheet to minimize backscatter radiation incident on the screen for electronic imaging. The screens are 0.020-in. tungsten permanently mounted with epoxy to stainless steel frames. The frames, with the screens, are removable so that either tungsten or tungsten/phosphor screens can be used. A careful stress analysis should be performed on the mounted screen configuration during the final design of the detector to ensure that the screen holder design is adequate to prevent stress concentrations at the point of screen attachment when the screen chambers are pressurized to 0.1 psi.

The changer will use standard 14-in. wide roll film. From Kodak, for example, types AA, T, M, and Ortho G, among others, are available in 14-in. wide rolls. The use of Ortho G film with tungsten/Gos:Tb screens can give a speed increase of at least 20X over type AA film with tungsten screens.[12]

Both side panels of the detector enclosure will be removable to provide access to detector components for repair or maintenance and to make it possible to change film from either side.

Figure 20 shows the package outline and location of the fields of view for film and electronic imaging. The estimated weight of the detector is 1800 lb. In addition, a 6½-in. thick lead beam stopper immediately behind the detector is required in order to reduce shielding requirements elsewhere as discussed earlier.



FD 137961A

Figure 20. Detector Package Outline

The film-transport simulation program[1] which was written to analyze the TELS film changer was used to analyze this changer since the film advance requirement for it is 24 in. compared to 14 in. for the TELS changer. Figures 21, 22, and 23 show the changer characteristics (i.e., film position and film tension vs time from turn-on of film-advance motor) for, respectively, frame number 1 (all film on the feed reel), frame number 50 (equal amounts of film on the feed and take-up reels), and frame number 100 (all the film on the take-up reel). As is evident from the film-position curves, the time for film advance is about 300 ms. This is the time interval between the turn-on of the film advance air motor and the stopping of the film motion after the air motor has been turned off. Because less film tension is required for this detector than is required for the TELS detector (since operation at 18g is not necessary), this film advance time of 300 ms for 24 in. of film advance is about the same as the time required for the TELS detector to advance the film 14 in.

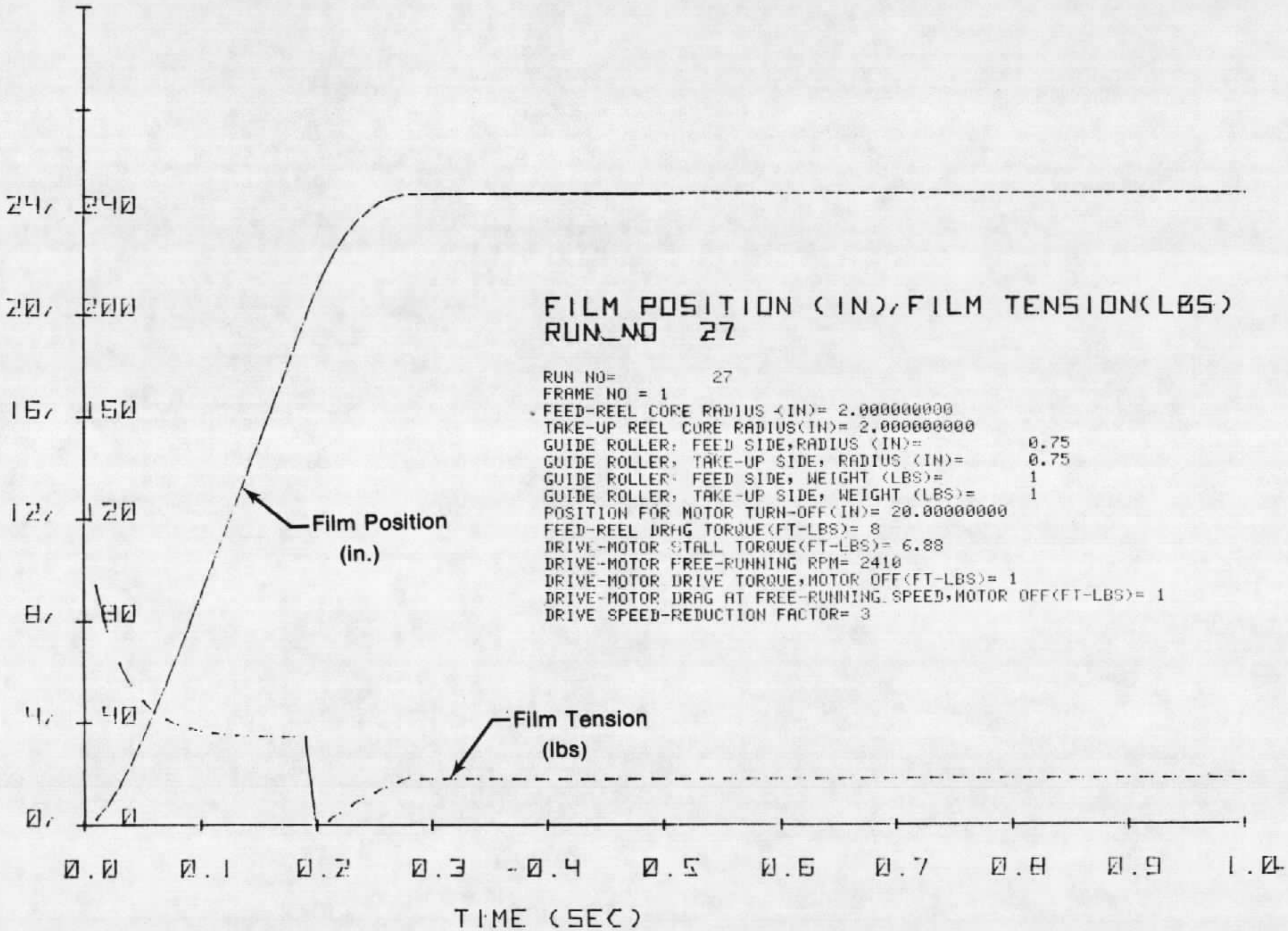
The screen actuation time is expected to be 30 ms plus the valve actuation time. The 30 ms figure is based on a moving mass of 50 lb, an actuation distance of 0.5 in., and a piston force of 300 lb. The valve actuation time is expected to be on the order of 40 ms. The time for one cycle which includes opening the screens, advancing the film, and closing the screens is, therefore, expected to be on the order of 500 ms.

The detector enclosure itself will require cooling. The allowable inside temperature for the film, for a thermal exposure time of 2 to 3 hr, is about 100°F. The maximum allowable operating temperature for the camera tube is 120°F, but it is cooled by a separate cooling system. Water cooling and temperature control will be required to maintain the detector interior between 80 and 100°F.

4.4.2 Optional Detector Array

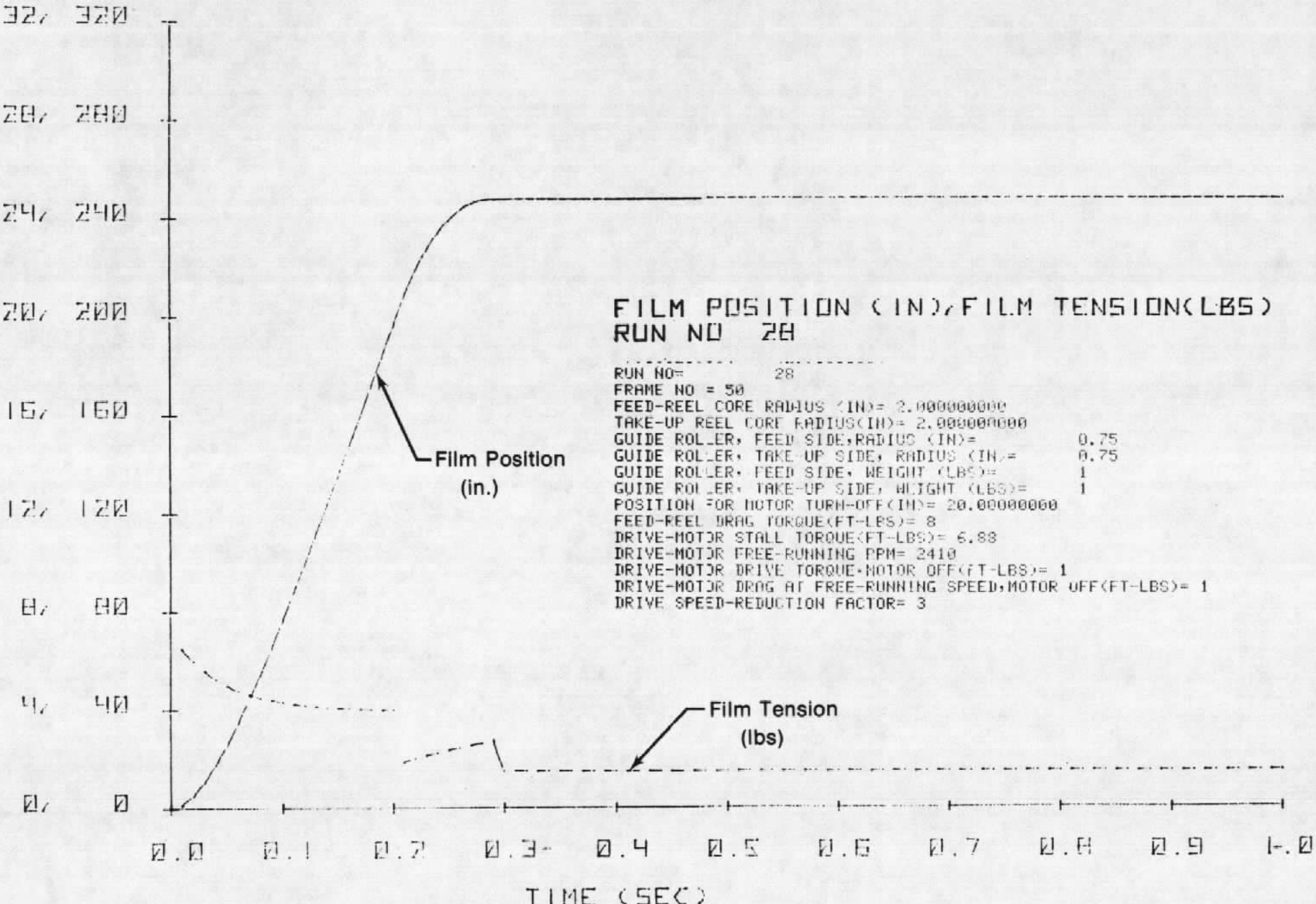
For rocket motor testing, it may in some cases be desirable to observe the propagation of the flame front over a large fraction of the burn duration. In order to obtain the wide field of view and to cover the large dynamic range in intensity required to do this, an array of three detectors is suggested. These detectors would incorporate electronic imaging only — no film changers. The field of view of each detector (figure 24) is 12 by 16 in.

Internal detector components are mounted on a subchassis. The outer enclosure is evacuated and the subchassis shock-mounted for noise and vibration isolation. Each detector drives a monitor for real-time viewing and a video tape recorder for subsequent processing of the data. Gain changes are effected independently and automatically via dose rate monitoring with separate internal detectors. Figure 25 shows the detector array in a typical configuration in test cell J-5.



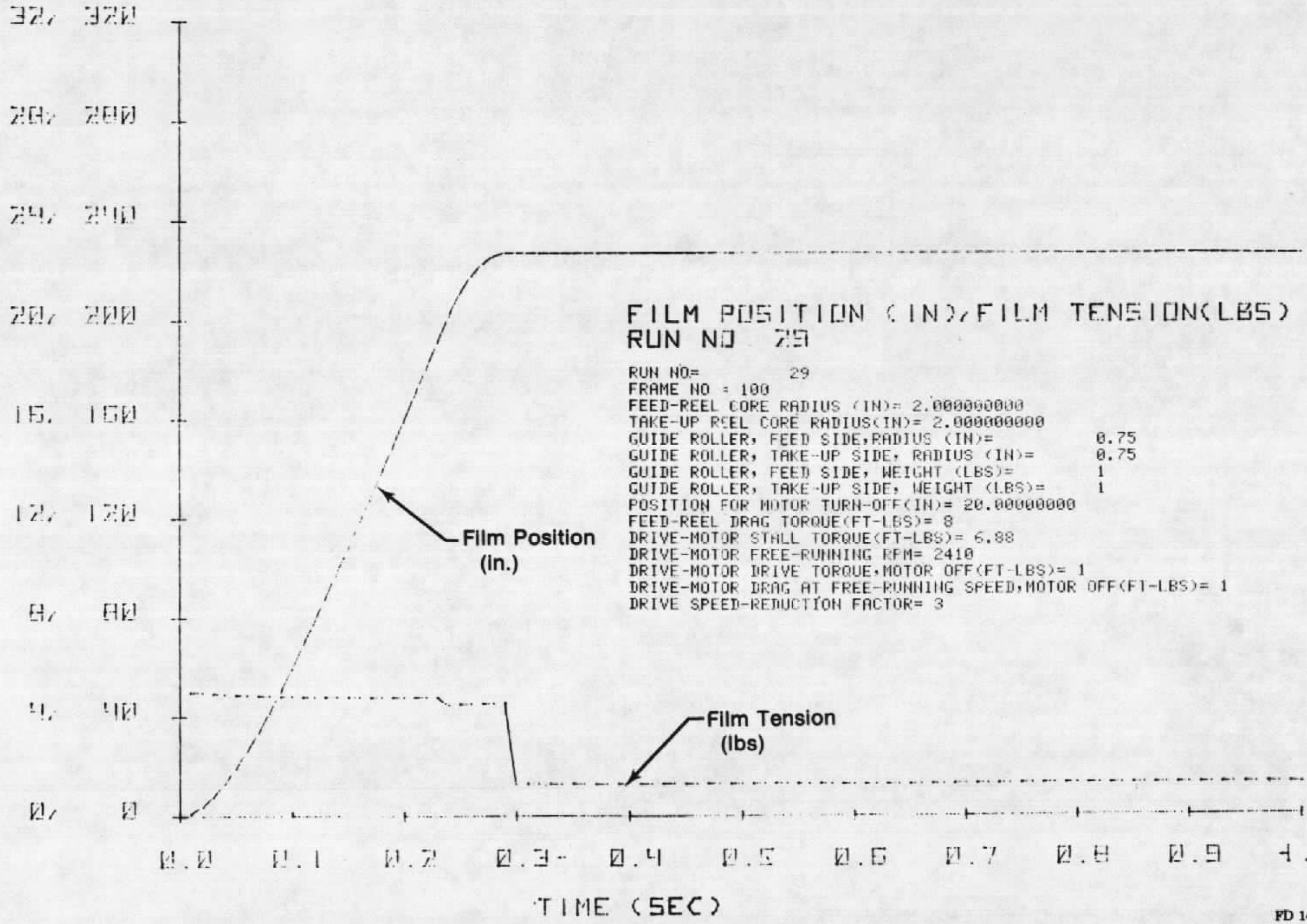
FD 144831

Figure 21. Calculated Film Changer Characteristics, Frame No. 1



FD 144832

Figure 22. Calculated Film Changer Characteristics, Film No. 50



FD 144833

Figure 23. Calculated Film Changer Characteristics, Film No. 100

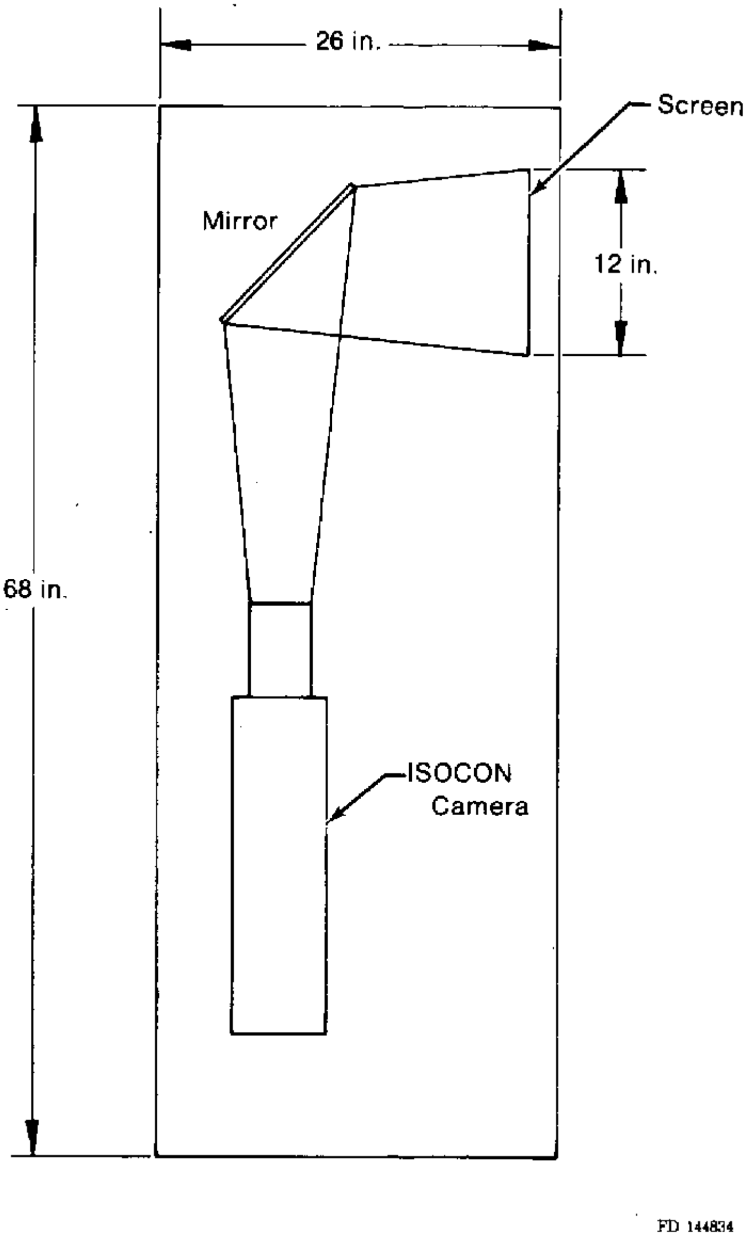


Figure 24. Optional Detector, 12 by 16 in. Field of View Electronic Imaging Only

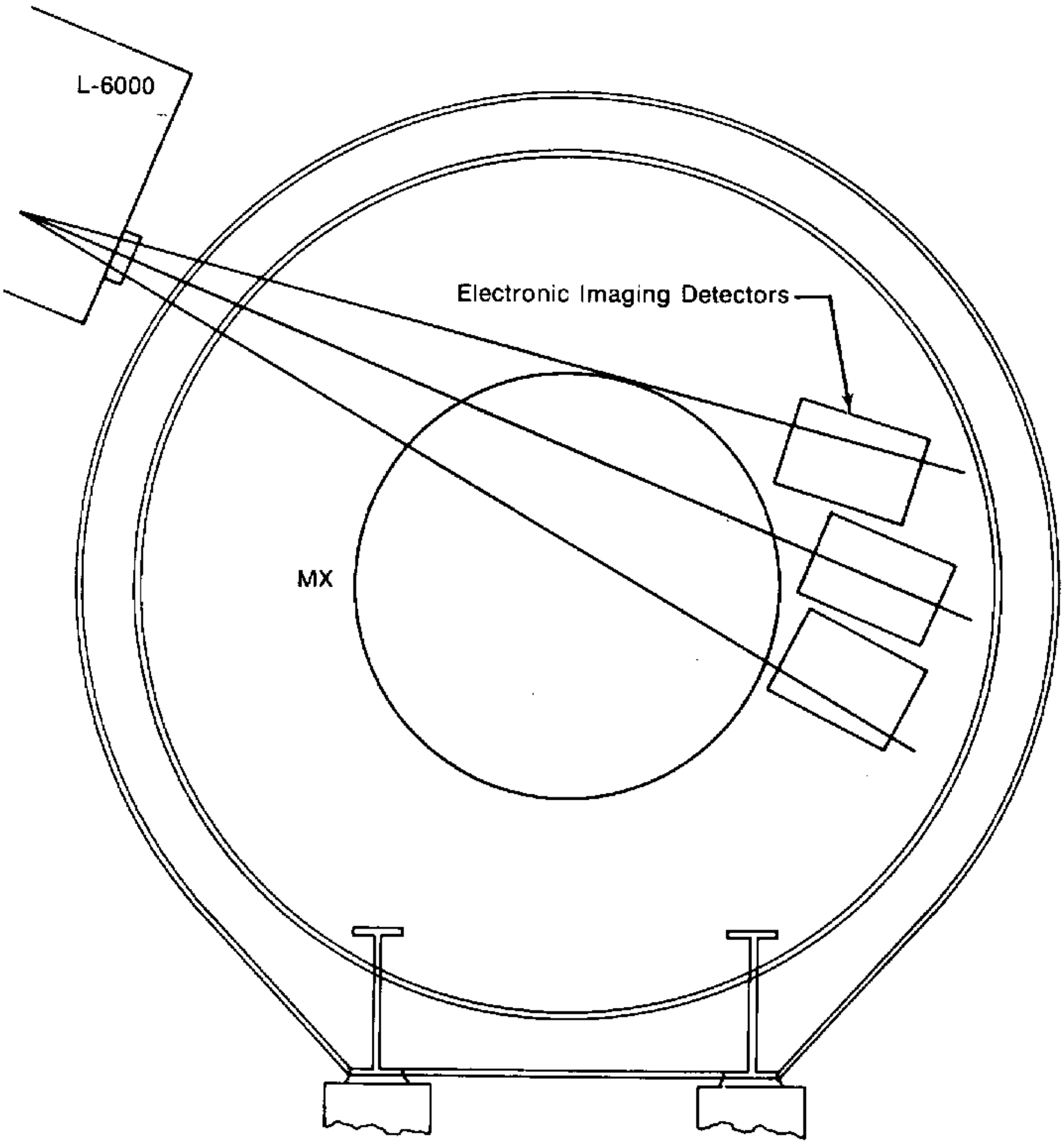


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Figure 25. Proposed Optional Imaging With MX 92-in. Diameter Motor in Test Cell J-5

4.4.3 Services and Controls

Figure 26 shows a layout of the detector services and microprocessor based controller for the radiographic system. It is essentially identical to the layout for TELS. Three channels of automatic exposure control are included, however, to accommodate the optional detector array. Not shown on this layout but also required are cooling water and temperature monitoring and control for the detector, as indicated in paragraphs 4.4.1, and for the detector heat shield, as indicated in paragraphs 4.9.3. The operation of the film changer is evident from this schematic and is also identical to the operation of the changer for TELS.

The computer (microprocessor) system is shown in more detail in figure 27 in which tasks have been partitioned according to the nature of the Input/Output transmissions. Bit-oriented tasks include the tasks:

- Sense if a switch is open or closed
- Turn a component on or off
- Sense if a component is on or off
- Turn an indicating lamp on or off.

These simple operations are best handled through the input/output (I/O) ports of the microprocessor. The microprocessor can set or reset either single bits individually or a number of bits simultaneously.

Byte-oriented tasks include reading, sending, and displaying multidigit data such as readouts from position encoders. These tasks are most conveniently handled by a structured bus-type data path. Information passes back and forth on the data bus in a bit parallel, byte serial fashion. Additional lines control the switching of the data path. The operator interfaces with the computer through the displays and bidirectionally through the teletypewriter (TTY).

A position-control interface will be required for each positioning component for the source and for the detector. The computer will receive digital positioning information from the interface and send digital positioning information to the interface. The interface itself will pool the sensors, limit position range, control some displays, and provide signals as required for servocontrolled motion to a new target position.

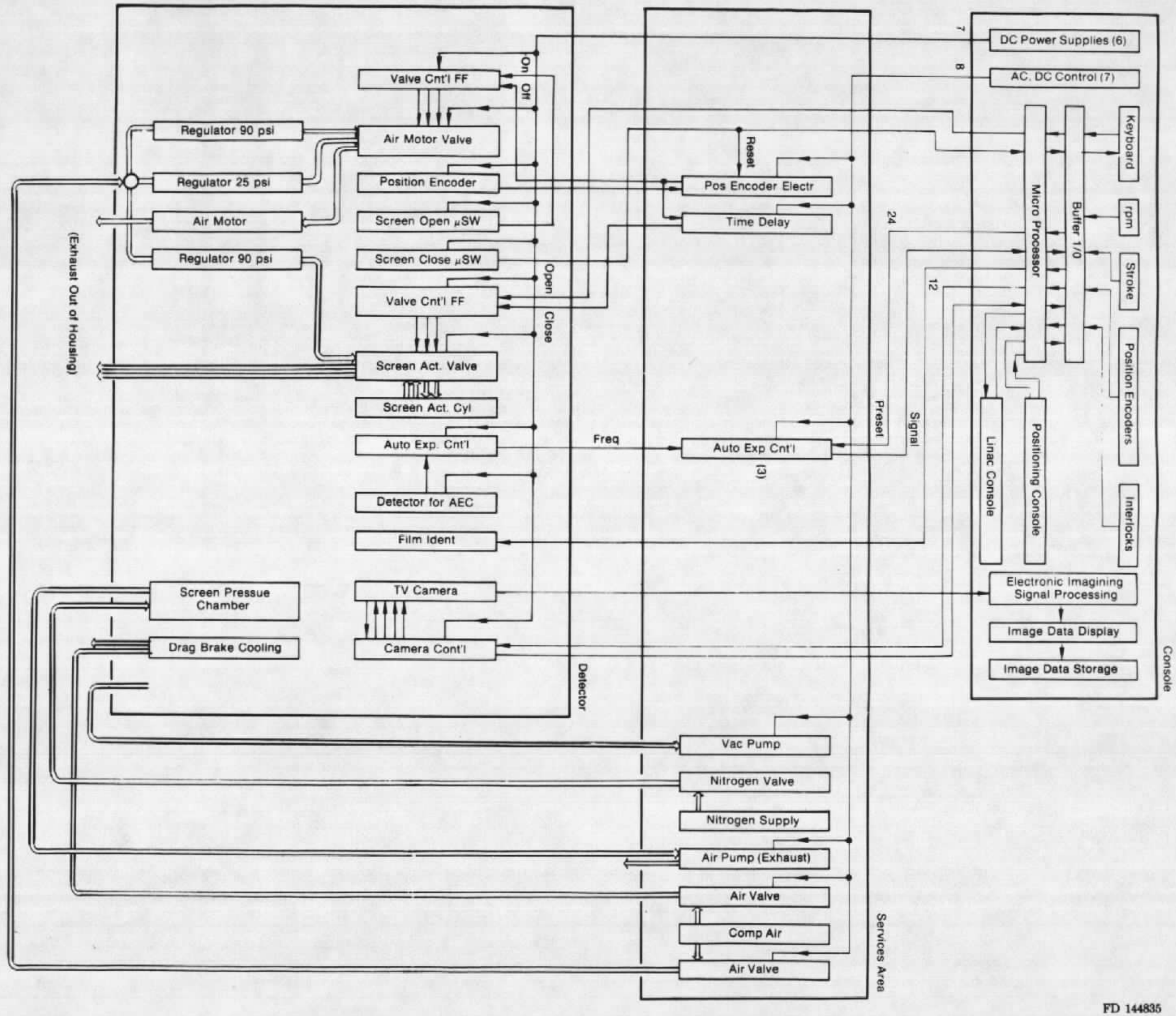


Figure 26. Services and Control Layout

1. Block Schematic of the Computer System

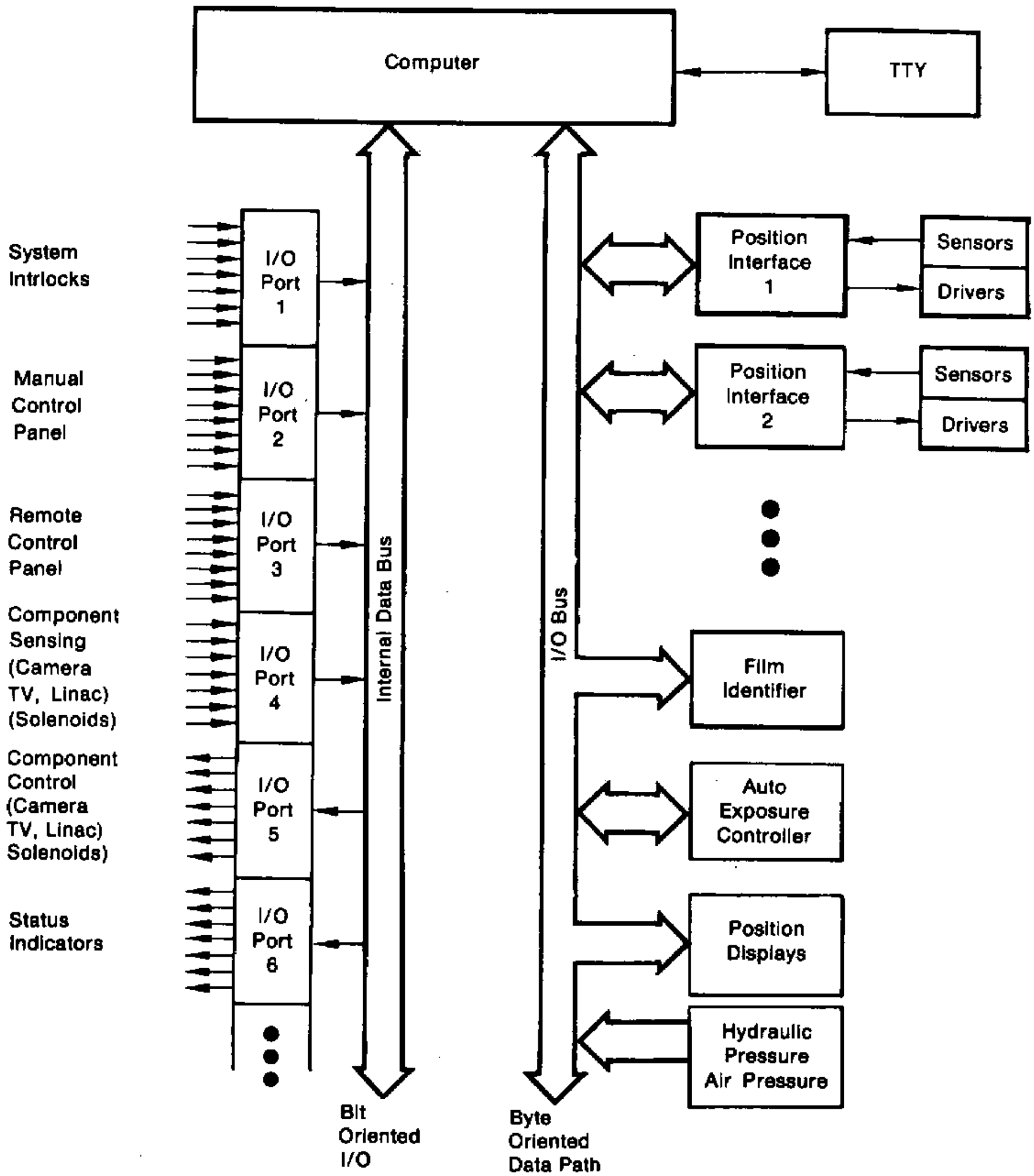


Figure 27. Partitioning of Computer Tasks

A typical microcomputer system for this application is Intel 80/20. The following components would be required:

- The system 80/20 including SBC 80/20 with 2K bytes random access memory (RAM), 4K bytes read-only memory (ROM)
- SBC 416 16K bytes programable read-only memory (PROM)
- SBC 519 Programable I/O Board (2 required)
- SBC 530 TTY adaptor
- Teletypewriter.

4.4.4 Console Space Requirements

The following list gives approximate space requirements for imaging-systems components to be mounted in the console.

1. *Readily Accessible*

• 12-in. monitor	15 in.
• Status lights panel	15 in.
• Video camera control unit	12 in.
• Teletypewriter	15 in.
• Video tape recorder	12 in.
• Waveform monitor	9 in.
• Manual control panel	12 in.

2. *Somewhere in Console*

• Computer	24 in.
• Dose monitors	24 in.
• A to D and D to A converters	12 in.

4.5 System Operation

4.5.1 Modes of Operation

The radiographic system will be capable of three modes of operation. In the manual mode, the system is controlled either from the manual control panel in the console or from a remote

control panel located at the test cell. The manual control panel will be used for manual control (via the computer) of the radiographic system during a test. The remote control panel will be used before a test to manually position the source and detector in a series of steps which can be remembered by the computer for use in automated repositioning during the test.

In the fully automatic mode, an entire test sequence, including operation of the source, detector, and positioning system, will be run under computer control. The test program will be entered from the teletypewriter, and the teletypewriter will provide status information during the duration of the test.

In the piecewise automatic mode, certain sequences of operation, such as repositioning operations, or operations for radiographic exposure sequences, will be stored in the computer, pretested, and used during an actual test. In this mode, the operator will manually initiate a particular programed operational sequence. The sequence will then be executed under computer control. When the sequence is completed, manual control is restored. The operator may have several sequences of operations stored in memory and available for use during the test.

4.5.2 System Check

The computer will control a pretest system check including verification that all equipment is turned on and that all services (electrical, hydraulic, pneumatic, etc.) for the source detector and positioning system are functional. It will also check that the film changer has film, that the system interlocks are closed, etc. The computer will also direct a pretest sequence in which the source and detector will be operated in order to ensure proper functioning. In the case of malfunction, the computer will provide system diagnostic analysis.

4.5.3 Compatibility with TELS

The imaging system hardware and operation will be compatible in the sense that the TELS detector could be substituted for the test cell detector. The detectors will probably use different type camera tubes for electronic imaging. Use of different camera tube types will require use of different camera control units in the console. The cabling can however be identical for both systems, with electrical interlocking provided to ensure that the camera control unit cannot be turned on unless it is the appropriate unit, and in the case of connection of the wrong unit, inability to turn it on would be sensed during system check-out by the computer.

4.6 Data Analysis

4.6.1 *Computer Processing*

Imaging system data would consist of film radiographs and videotape from the electronic imaging system. A data analysis facility will be required to process data from the TELS and the test cell radiographic systems. Data on film will be scanned, digitized, and computer processed to obtain desired measurements such as seal clearances in the case of turbine engine data. Data on videotape can be digitally integrated as desired, trading off signal-to-noise ratio against time resolution, to obtain the best image quality. Videotape data can be digitized and entered into the computer for analysis. Some on-line processing of data from the electronic imaging can be provided.

4.6.2 *A Typical Case — Measurement of the MX Nozzle Throat Diameter*

An X-ray transmission calculation across the nozzle throat plane of a 2nd-stage MX motor was performed in order to estimate the sensitivity for measuring the nozzle throat diameter. This was a first-cut calculation and an idealized, cylindrical geometry, which ignored propellant fins, etc. A Hercules preliminary design incorporating a submerged nozzle with three-dimensional (3-D) carbon throat insert was used, and is assumed to be a typical design for this purpose. Figure 28 shows a cross-sectional view of this nozzle. A line has been added to indicate the approximate location of the inner surface of the propellant before the burn starts.

The transmitted X-ray flux was calculated for a pencil beam of X-rays in a plane just to the left of the throat plane (i.e., through the carbon phenolic rather than through the aluminum), as a function of the displacement of the pencil from the center of the nozzle. The results are shown in figure 29. The R_1 is the radius of the uneroded nozzle; R_1' is the nozzle radius after 0.250 in. of erosion. The R_2 is the radius of the interface between the 3-D carbon and the graphite phenolic. The R_3 is the outer radius of the carbon phenolic at the throat plane. The R_4 is the inner radius of the propellant, which is taken as 15.15 in. at the start of the burn, and 20, 30, and 40 in. at later times as the burn proceeds. The R_5 (not shown) is the outer radius of the motor and is taken as 46 in. The X-ray source is a 6000 rad/min, 15 MeV linear accelerator, and the source-to-film detector distance (SFD) is 200 in.

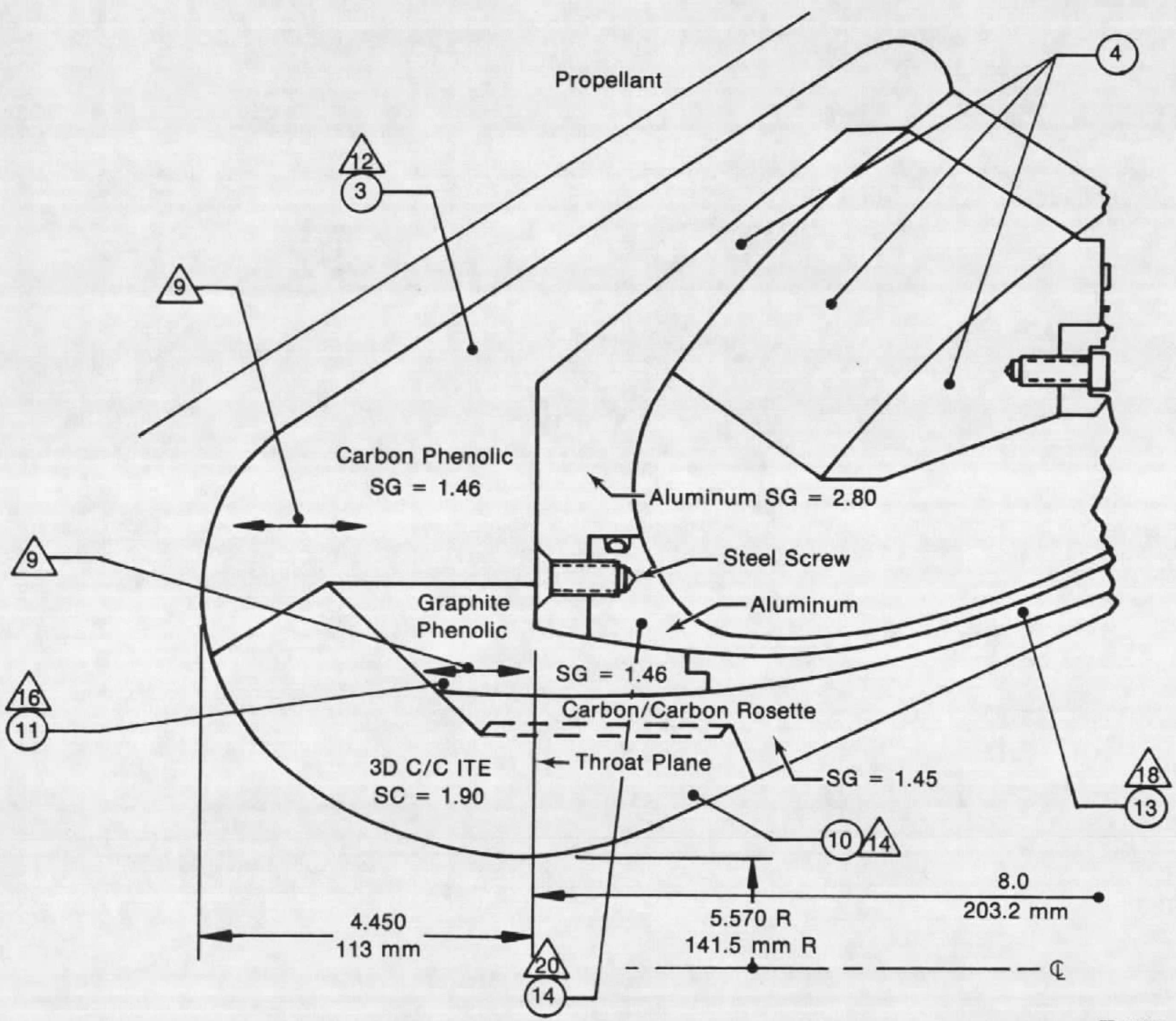


Figure 28. Hercules S/S MX Nozzle, Preliminary Design

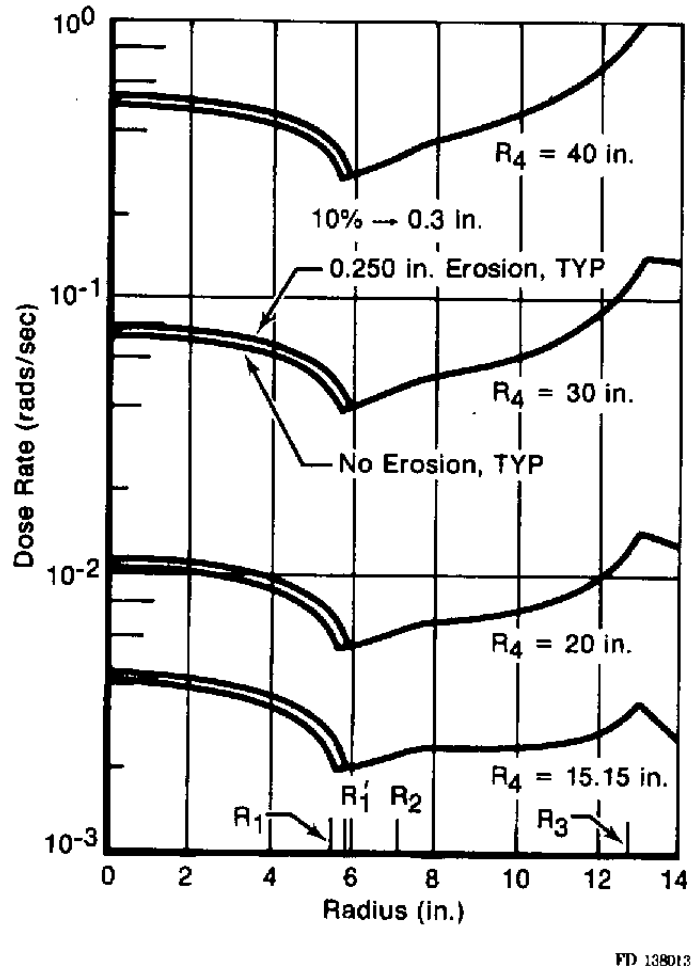


Figure 29. Calculated MX Nozzle X-ray Profile

At the beginning of the burn ($R_4 \sim 15$ in.), the dose rate at the detector is at its lowest value and is on the order of 2×10^{-3} rad/sec. Using a fast screen/film detector system, an exposure to a film density of H&D2 can be obtained with a dose of 12 mrads. Therefore, even at the beginning of burn, an exposure to obtain a film density of H&D2 can be made in less than 10 sec with a fast screen/film detector system. Determination of the nozzle throat diameter is made by fitting the measured film density profile to the calculated profile using regression analysis by the method of least squares.

4.7 Maintainability

Both sides of the detector will be removable for good accessability to internal components. All connections between the bulkhead in the outer enclosure and the subchassis will be made with jumper cables and jumper hoses to facilitate removal of the entire subchassis. System verification and system diagnostics will be performed by the console computer.

4.8 Portability

All electrical cables and services such as compressed air and vacuum can be disconnected at a bulkhead in the detector outer enclosure. The detector can then be unbolted from the positioning system, placed on a truck with a thick foam pad on a truck bed, and transported between test cells without removal of any internal components. However, as indicated in paragraphs 4.4, care must be taken to ensure that the detector is never turned in such a way that the isocon camera tube would be tilted faceplate down.

A portable services module can be used to supply compressed air, dry nitrogen, and vacuum pumping for the detector. The module can be placed near the test cell and a test cell port with bulkhead connectors used to bring these services inside the test cell.

4.9 Survivability

4.9.1 Overpressurization

The only test cell in which overpressurization is expected to be a possible problem is J-5. The hatch cover on J-5 will start to lift off if the internal pressure exceeds atmospheric pressure by more than 1 psi. Since the detector is evacuated internally, this would correspond to 16 psi of overpressure on the detector. The pressure inside J-5 should never exceed 16 psi by very much except possibly for very short transients.

The approach to providing protection for the detector in case of overpressurization is to allow the walls to deflect inward and maintain sufficient clearance inside so that they do not contact and damage internal parts.

For a beam uniformly loaded with pressure p and supported at the ends, the deflection at the center is:

$$y = \frac{pw}{EI}\,\frac{5}{24}\left(\frac{\ell}{2}\right)^4 \tag{18}$$

Where, w = width of beam

ℓ = length of beam.

The modulus for 6061-T651 (weldable) aluminum alloy is $E = 10.0 \times 10^3$ ksi. The cross-sectional moment of inertia of the beam about the neutral axis is:

$$I = wt^3/12 \tag{19}$$

in which t is the thickness of the beam. The clearance between the outer enclosure and the subchassis, and therefore the allowable deflection, is 0.5 in. If the beam length is 28 in., corresponding to the width of the detector, and the beam thickness is 0.75 in corresponding to the detector wall thickness, then the overpressure required to cause contact with the subchassis is p = 22 psi.

The section of outer enclosure covering the detector screens will be removed and the opening covered with a 0.060-in. thick aluminum sheet. The width of the opening will be 16 in. and the length will be 26 in. If we assume that the length is long compared to the width, then the cover will deform with overpressure into a section of cylinder of radius (R) and the force per unit length along the edges will be N = pR (figure 30). The arc length is the original length ℓ (the "width" of the opening) times $(1 + \epsilon)$. ϵ is the strain. In terms of the radius of curvature (R), the arc length is $2\alpha R$, so

$$(1 + \epsilon)\,\ell = 2\,\alpha R.$$

Also, $R \sin \alpha = \ell/2$. For small α,

$$\sin \alpha = \alpha - \alpha^3/3!,$$

so $\epsilon \approx \alpha^2/3!$ The force N is the stress (σ) times the membrane thickness (t) and the stress is the modulus (E) times the strain (ϵ), so $N = E\epsilon T = pR$. Substituting for E, using $R \approx \ell/2\,\alpha$, and solving, we have:

$$\alpha^3 \approx \frac{6\,p\ell}{2tE}. \tag{20}$$

So for 22 psi of overpressure R = 16 in., t = 0.060, and $E = 10^7$ psi, we find that α is 0.12 and ϵ is ~ 0.002. For 6061-T651 aluminum the strain to yield is 0.004 so the cover will survive the 22 psi of overpressure. The deflection at the center is ~ 0.5 in.

4.9.2 Protection Against Flying Objects

In the area of the screen, the detector will be quite vulnerable to flying objects. In other areas it is feasible to provide some protection. Assuming that a turbine section of radius 2 ft and rotating at 15,000 rpm breaks apart, then projectile velocities of approximately 3000 ft/sec can be expected. This is considered in the low-velocity region from the point of view of projectile penetration theory. Aluminum is not considered a good barrier for projectiles in this velocity range because it tends to crack and break up. Lexan (polycarbonate resin plastic) is a very good

material for absorbing impact. A ½-in. thick piece of Lexan by itself will stop a 45 caliber slug (traveling at 2000-3000 ft/sec). Our approach to this problem is to cover the outside of the detector, except the area in front of the screen, with a 0.5-in. protective layer of Lexan. This layer should greatly reduce detector vulnerability to flying objects.

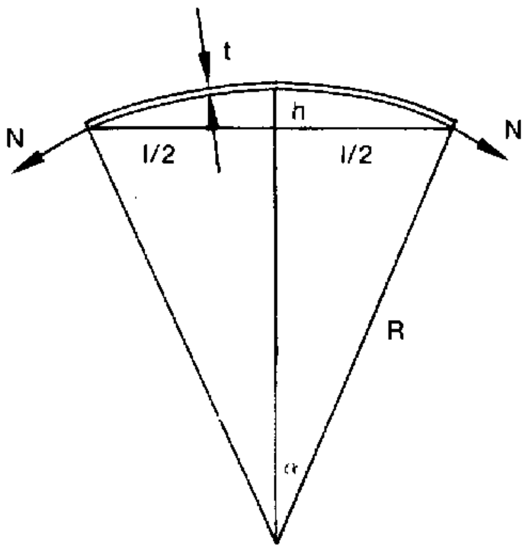


Figure 30. Arc Length of Outer Enclosure

4.9.3 Protection Against Plume Radiation

A rough order of magnitude for the incident radiant energy on the detector was obtained for the case of the detector positioned for viewing in the nozzle throat plane of a C-4 motor. C-4 flight data were used to make the estimate and the result was a maximum of 2-4 Btu/ft²/sec incident on the detector. Half of this incident heat derives from reflectance of plume radiation from the walls of the test chamber.

This level of thermal radiation is high enough to damage the Lexan protective layer on the outside of the detector. Even with aluminum reflective tape over the Lexan, the absorbed energy will probably be sufficient to cause damage. The relevant Lexan properties are the melting point $T_g = 150°C$, the thermal conductivity $k = 4.6 \times 10^{-4}$ cal/sec cm²/(°C/cm), the specific heat $C_p = 0.28 - 0.30$ cal/°C/g, and the specific gravity = 1.2.

Four Btu/ft²/sec corresponds roughly to 1 cal/cm²/sec. The surface temperature for a constant flux of heat F_o input at the boundary of a semi-infinite solid initially at zero temperature and having diffusivity κ = K/C is:[12]

$$T = \frac{2F_o}{K}\left(\frac{\kappa t}{\pi}\right)^{1/2}. \tag{21}$$

Therefore, if all the incident radiation were absorbed, the Lexan surface temperature could go to about 900°C for a burn duration of 100s. However, if 90% of the incident radiation were reflected by the aluminum tape reflector, then the surface temperature would only go to ~ 100°C for a 100s burn duration, which would be acceptable. Adequate thermal shielding for this case could be obtained by applying aluminum tape to the entire detector and providing a shadow shield on the plume side of the detector. However, such a shield may not be adequate for turbine engine testing because of the longer test duration.

Without an afterburner, the jet engine exhaust plume will be approximately 1500°R (1040°F). This temperature is much lower than that of the rocket engine plume but the detector may be positioned closer to it. With an afterburner, the temperature inside the afterburner can be as high as 3200°R. At altitude, the plume expands and cools. At 30,000 ft, the expected plume temperature with afterburner on is on the order of 2000°R. At low altitude, the plume is confined and its temperature can approach 3200°R. Therefore, the radiant heat to which the detector is exposed could in some cases approach that level expected in rocket-engine testing, but with much longer duration involved.

The conclusion is that a removable, water-cooled, heat shield is required for placement on the plume side of the detector. This shield must be monitored for water flow and temperature by the radiography control system.

SECTION 5
POSITIONING SYSTEM
(P&WA)

5.0 GENERAL

The ability to properly utilize the X-ray source and film detector to obtain meaningful data from an operating engine depends on a positioning system that will provide accurate interaction between the X-ray elements and the test article. Basically, the positioning design must provide:

- Precise alignment of source/detector with test object
- Stabilized alignment of source/detector during testing
- Flexibility of movement around the engine.

Control of spotting the components must be accomplished not only manually at the test chamber, but also remotely from the control room. Source/detector repositioning during testing on a preprogramed computerized basis will increase the flexibility and capability of the radiographic program.

The Pratt & Whitney Aircraft portion of this study consisted essentially of integrating the source-detector-positioning components into a total radiographic system encompassing the operational criteria stated in Section 1.

5.1 MOUNTING/POSITIONING SYSTEM CRITERIA

Formulating a positioning plan for the altitude cells being considered under this study presented some unique problems in meeting the technical requirements of an effective radiographic system layout. The essential requisites of this type of test facility, which are normally found in most industrial applications, e.g., spacious areas around the test item for ease of source/detector positioning as well as the capability to manipulate the test object, were not available at the AEDC locations under this study. Tailor-made positioning concepts were required at each cell.

5.1.1 Space Available

All of the study facilities present a problem in working space. The J-1 and J-5 test cells have very small chamber diameters, i.e., 16-ft inside clearance and at J-2 this clearance is 20-ft ID. C-1/C-2 will be constructed to a larger 28-ft ID, but, compared with P&WAs engine X-ray location, this facility will have about 30% less cross sectional area. Internal equipment and

services at all test positions contribute to the clearance problem and will require considerable rearrangement and modifications for inclusion of any X-ray components.

5.1.2 Maneuverability of X-ray Equipment

At both the J-1 and J-2 (and presumably also at C-1/C-2) cells, the engine is suspended from a fixed overhead mount and cannot be rolled or otherwise moved. The X-ray apparatus must therefore circumvent the engine as much as possible. Specifically, the moves required for both the source and the detector can be described as:

- Axial (parallel to ℄ of engine)
- Radial (perpendicular to ℄ of engine)
- Vertical
- Tilt (hinge action in the vertical plan).

Another disadvantage encountered was the size of equipment in the existing family of commercial X-ray machines. Models operationally suitable for the altitude test requirements had weights ranging from 1 to 3T and volumes from 30 to 180 cu ft. A particularly critical dimension (length) of these sources severely limited the ability to position the equipment inside the chamber at the proper "focusing" distance from the engine. Recognizing that maneuverability was a prerequisite for successful radiography, it was decided to calculate the equipment performance not only (1) inside the chamber, but also (2) outside the chamber and (3) within a "bubble" addition to the cell clamshell to allow theoretical optimum placement (Table 1, Section 2). The latter two options provided better maneuverability than option (1) — the internal set-up.

The film detector was easier to handle than the source, but was required in all cases to be placed within the chamber for proper film exposure. The detector, by design, presented a relatively small critical length dimension (28 in.) as compared with the X-ray encasement.

5.1.3 X-ray Coverage of Engines

The ideal X-ray positioning system for jet engine and rocket motor coverage would be one that allows full 360-degree scanning capability along the full length of the test object coupled with the ability to rotate the object. This arrangement would permit a complete range of tangential and radial shots on the engine for full diagnostic inspection. Such ideal coverage is not possible, however, at any of the current locations. The overhead "strongback" engine mount in its fixed position obviously prevents 360-degree scanning as well as any capability to roll the object. This situation is similar to that at P8 where tangential shots are limited to approximately ±30 degrees from top dead center and bottom dead center of the engine.

Figure 31 illustrates the approximate coverage available for J-2 test cell using a typical inside-the-chamber X-ray installation.

5.2 X-RAY POSITIONING SYSTEMS

5.2.1 J-1 Test Cell

The J-1 test cell was the starting point for the P&WA/Florida detailed study for the radiographic positioning systems. This cell was recognized as being the most difficult to adapt for an X-ray inspection system considering its relatively small 16-ft inside clearance diameter coupled with the inherent fixtures and equipment within the chamber. A recent photo of this cell without an engine is shown in Appendix C. Determining a design for the J-1 would, of course, depend on which source and detector would meet the general requirements for turbine engine X-rays.

The detector selection proved to be quite simple. The conceptual design by LMSC for the J-5 detector format would perform quite satisfactorily in the J-1. Also, the size and weight of this item could be easily positioned within the chamber at the proper object-to-film distance.

For the source, the investigation of off-the-shelf hardware showed that none would operate satisfactorily for J-1 either inside or outside the cell. The "bubble" modification option would require extensive rework of the clamshell hatch along its full length for proper housing of the smaller LINATRON-2000 source. The use of commercial sources inside an unmodified J-1 cell was impossible due to lack of space. The exterior position option using the LINATRON 6000 (figure 32) showed unsatisfactory technical performance in several areas:

- Exposure times were considerably greater than the 1-sec minimum specified
- Object magnification at film exceeded the limit of 1.3
- Excessive radiation scatter within work area.

The TELS family of sources also proved to be unsuitable for J-1. The TELS "modified" X-ray concept, which was specifically repackaged for the limited space of the altitude chambers, was the only X-ray device adaptable to inside positioning (figure 33). However, it fails in technical performance due to excessive magnification and exposure times. The standard TELS design X-ray unit firing from the outside through a low attenuation aluminum window required an unacceptble exposure time of 5.1 sec for adequate radiographic pictures with a resultant increase in radiation scatter.

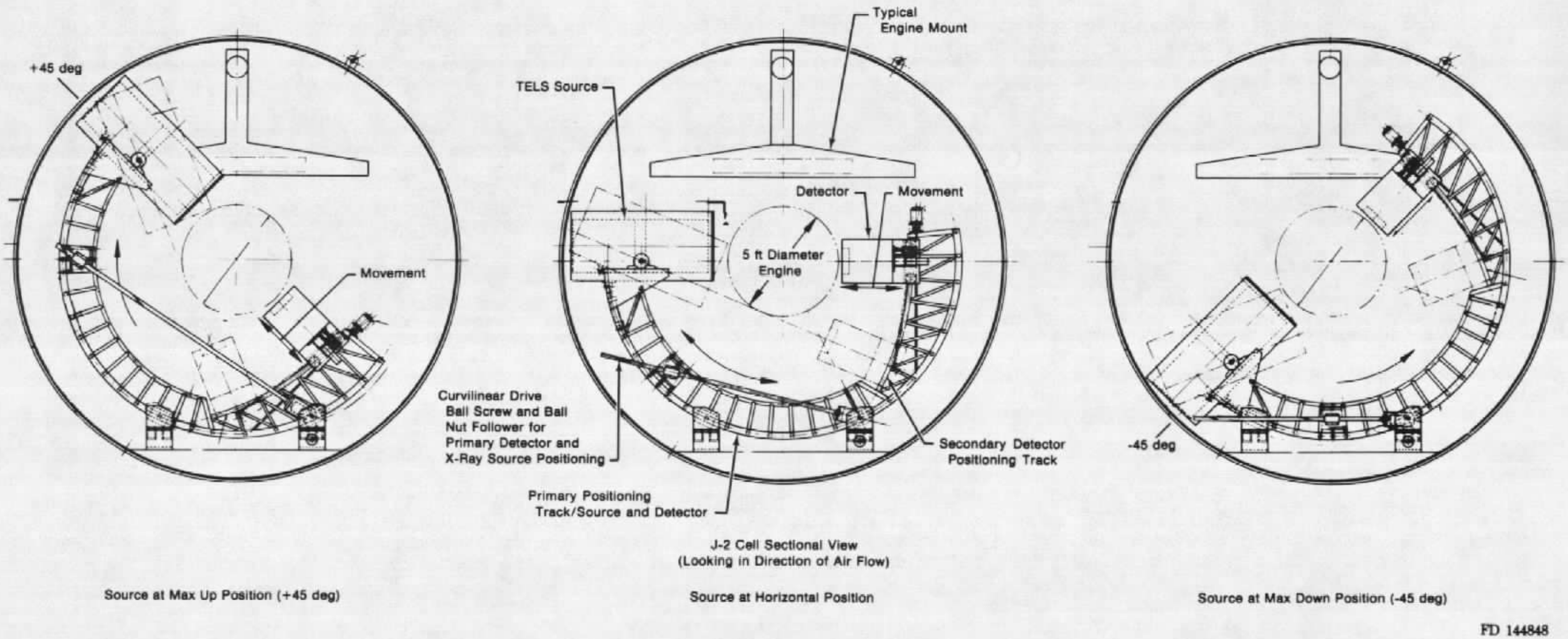


Figure 31. Available Coverage for J-2 Test Cell With Inside-the-Chamber X-ray Device

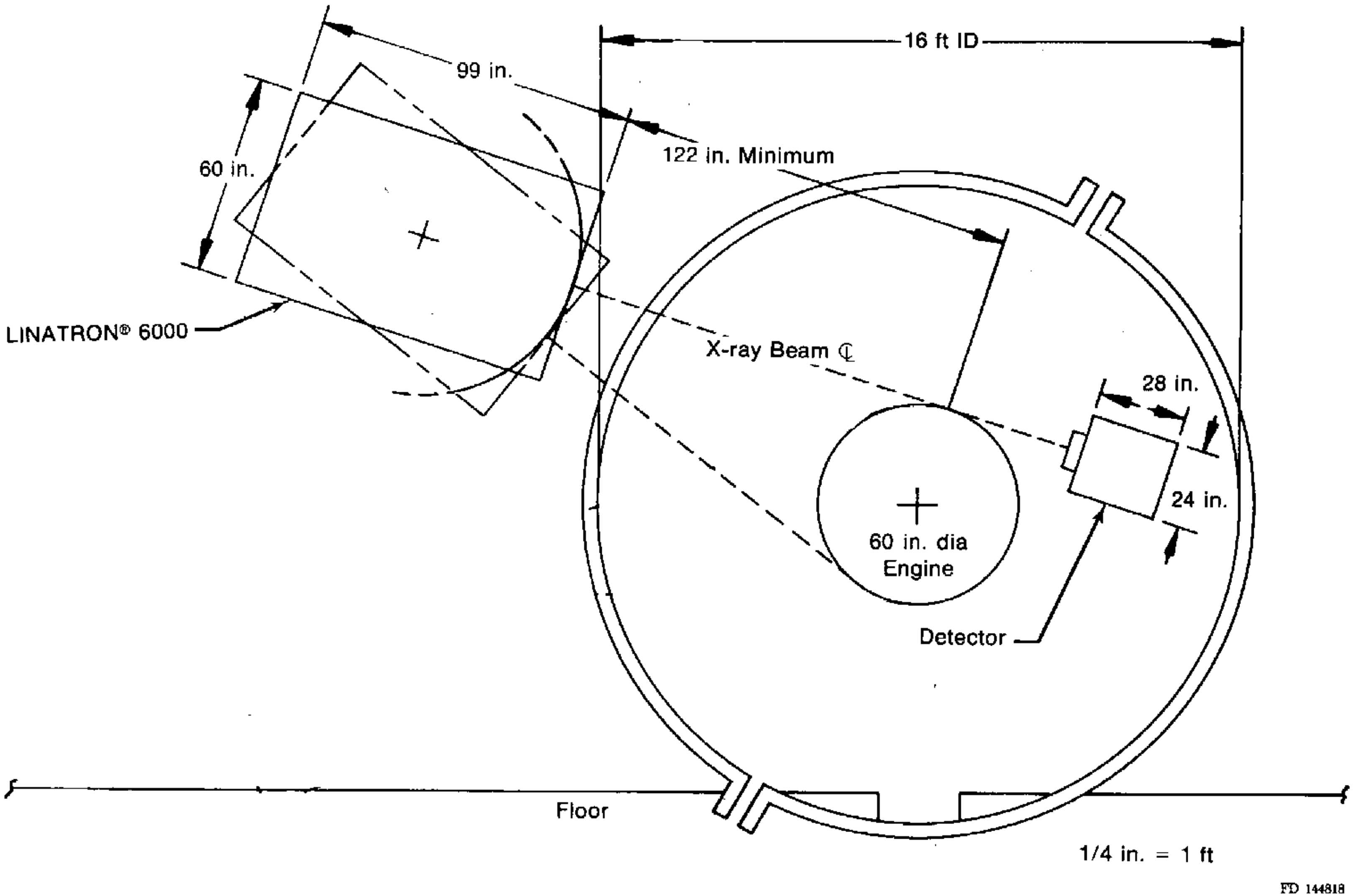


Figure 32. J-1 Test Cell Showing LINATRON® 6000 Source External to Chamber

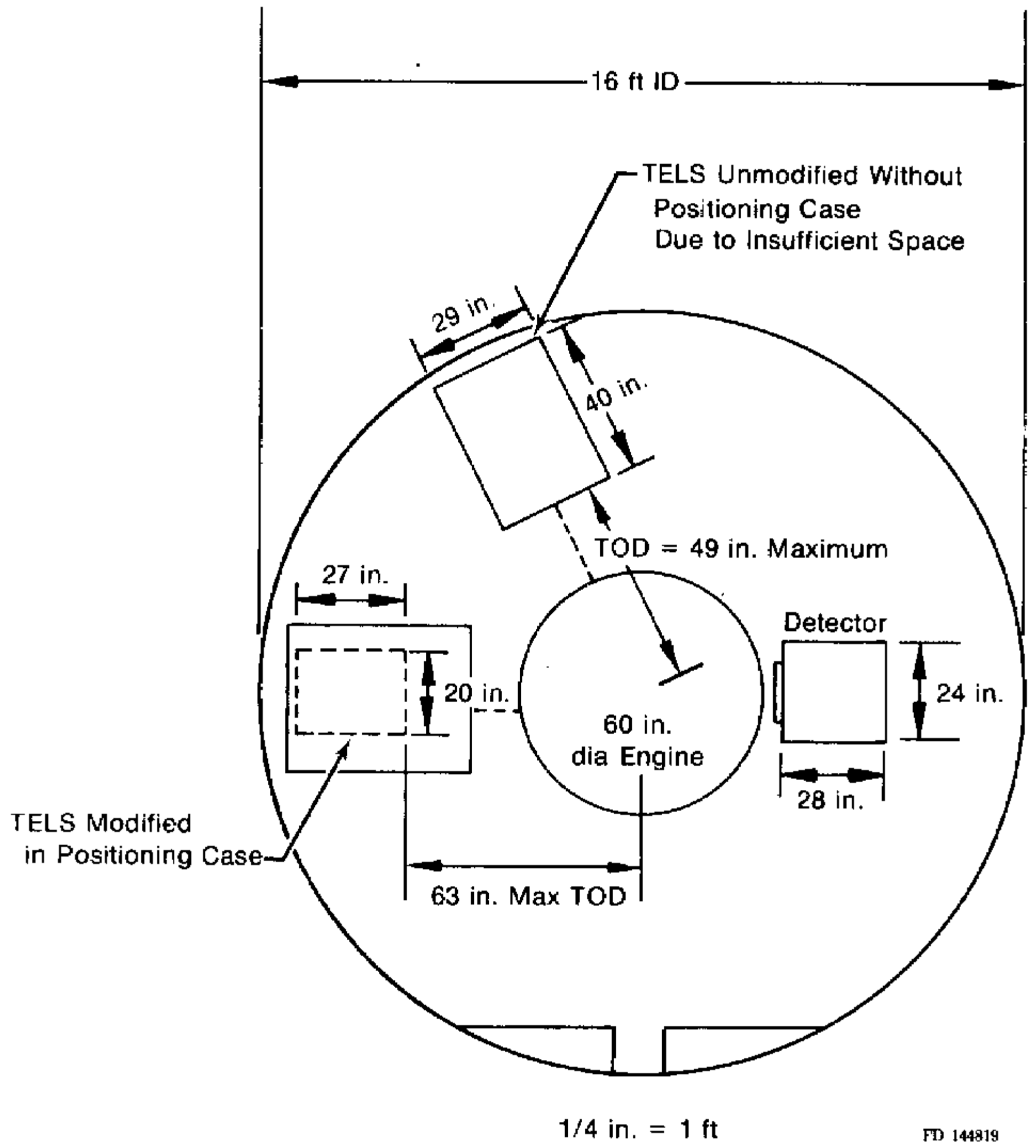


Figure 33. J-1 Test Cell Showing TELS Unmodified and TELS Modified Sources Mounted Internally

In view of the study findings concerning the J-1 facility noted above (e.g., inside cell space limitations, inadequate equipment performance, extensive cell modifications necessary for proper positioning of the source, etc.) it was concluded that J-1 was not a viable facility for a radiographic inspection system and should not be considered any further.

5.2.2 Test Cell J-2

J-2 test cell (figures 34 and 35) was recognized as being more closely suited to radiography than the smaller J-1. Its 20-ft diameter offered 56% more cross-sectional area than J-1 and considerably more capability for an operating positioning system.

Again, the commercial models were first considered for J-2 positioning, but none were suitable for inside location due to their large size. As covered earlier (Section 2), the TELS X-ray was selected as the only overall acceptable model for the J-2 chamber.

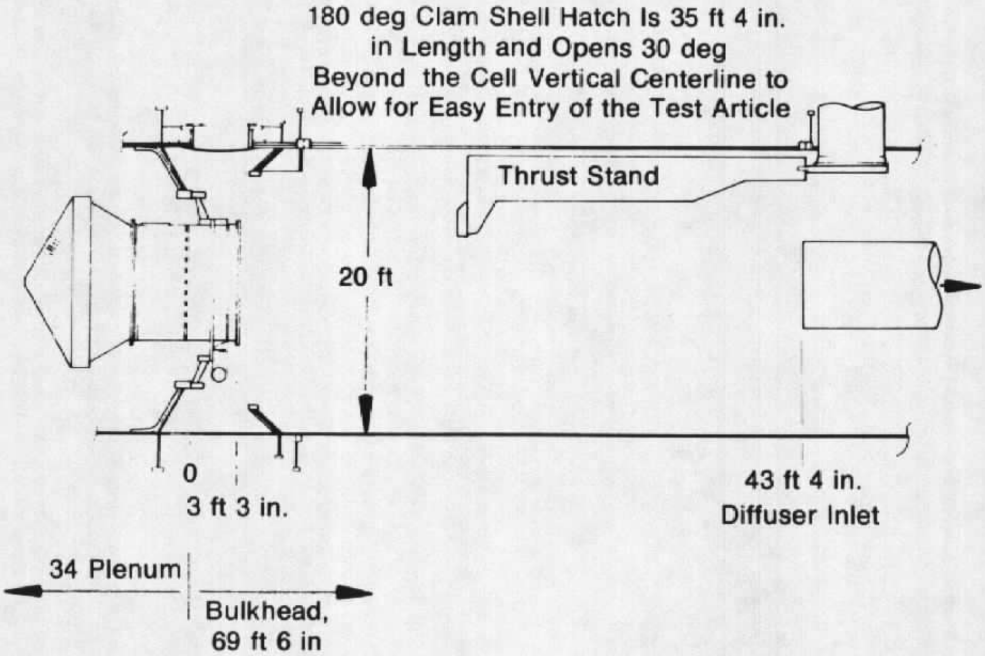
The positioning system concept for J-2 as shown in Pratt & Whitney Aircraft drawing JXP 3755 (figure 36) provides the necessary motions for the source and imaging detector, namely:

- Roll (partial around engine)
- Radial
- Tilt
- Axial (parallel to engine ℄).

The imaging system must maintain a perpendicular position to the X-ray machine to prevent distortion in the picture. The source and detector will roll as a unit; however, the detector can maintain the film normal to the X-ray beam by moving on the arc travel path of the secondary track.

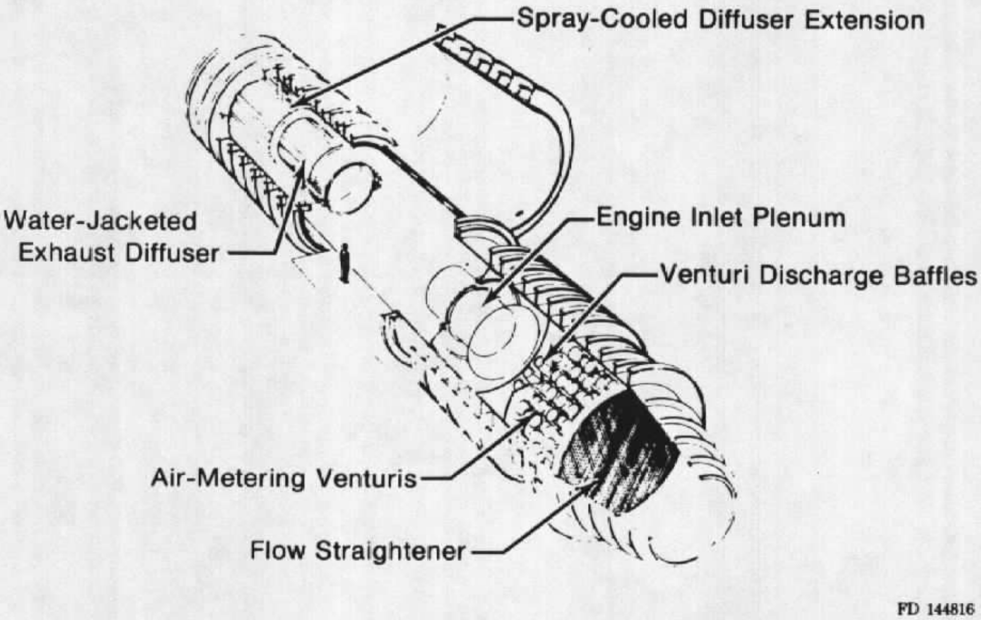
The TELS source is housed in a cylindrical casing which provides a mounting for the actuators for a radial travel of 34 in. This casing also serves as a protective shield for the X-ray unit against an engine failure during operation.

The detector is mounted directly to a pair of actuators which allow a radial move inward of approximately 6 in. As noted in figure 37 the primary beam stopper, 6.5 in. of lead shielding, is attached directly to the positioning mechanism rather than the detector itself.



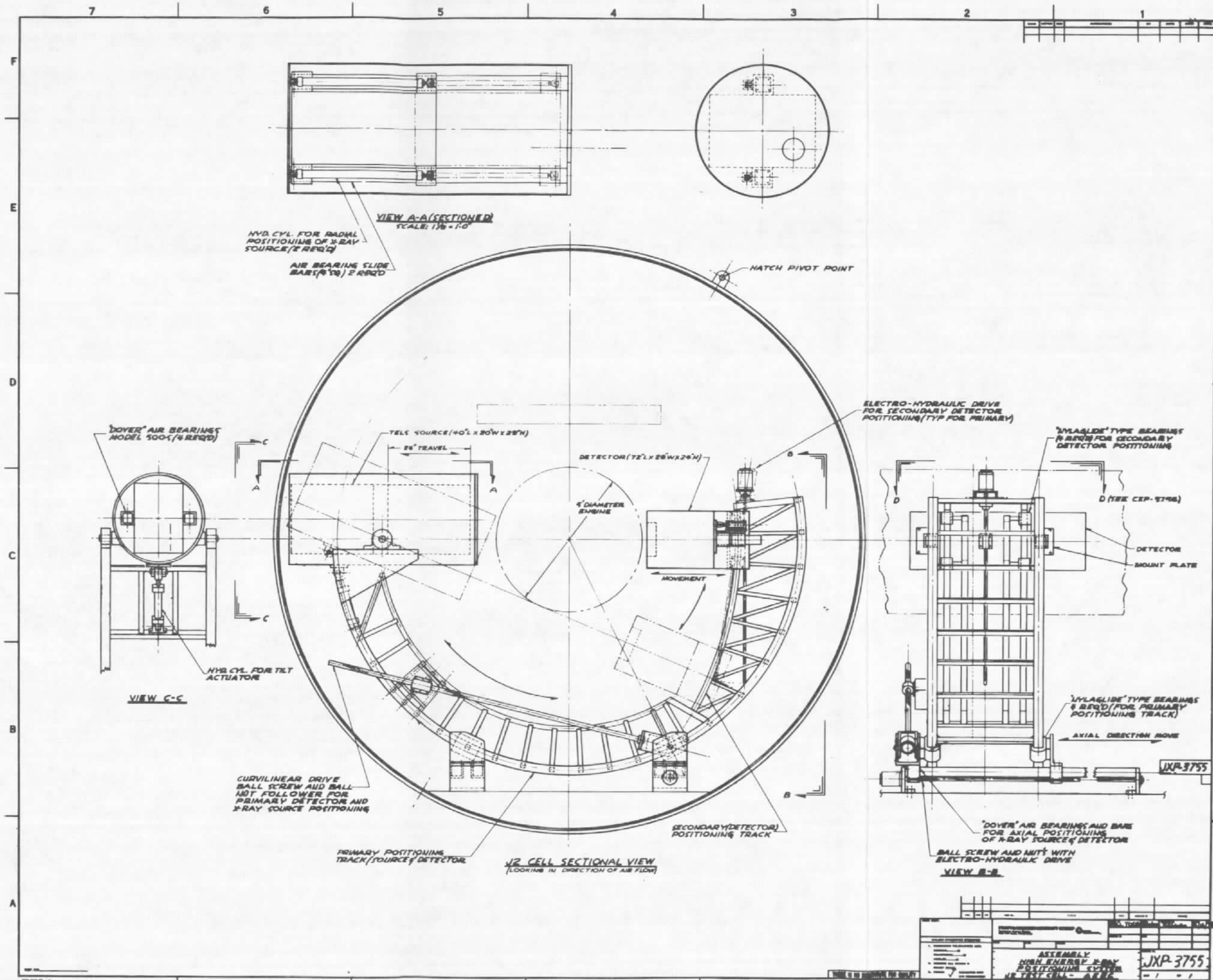
FD 144815

Figure 34. Clearance Volume for Test Article Installation for J-1 Test Cell



FD 144816

Figure 35. Propulsion Development Test Cell (J-2)



JXP 3755

Figure 36. J-2 Positioning System Showing Operating Motions for the Source and Imaging Detector

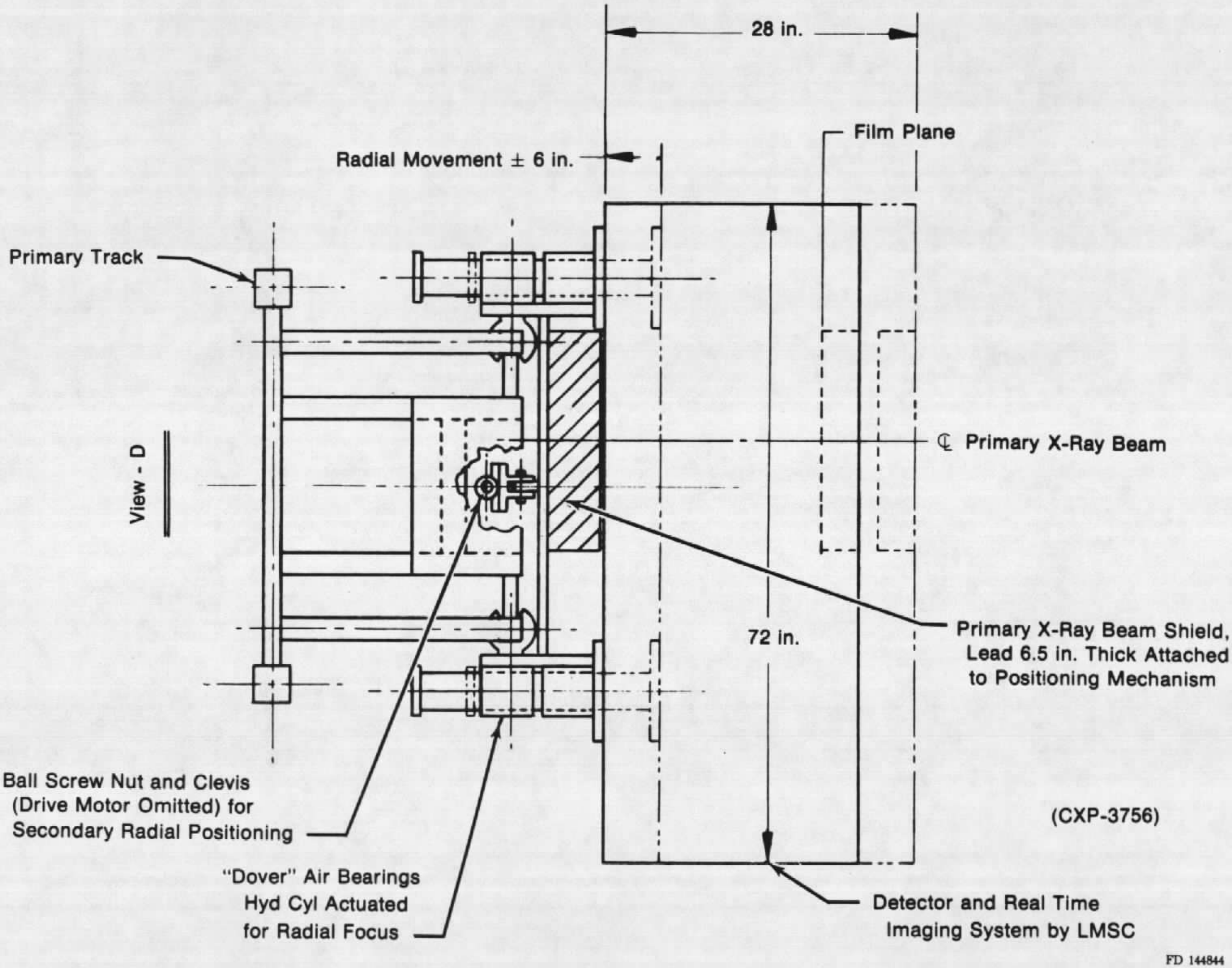


Figure 37. J-2 Detector Positioning Mechanism

5.2.3 Test Cells C-1/C-2

These cells are a part of the future Aeropropulsion Systems Test Facility (ASTF) now being constructed at AEDC. Both test chambers will measure 28 ft ID and offer considerably more space than either J-1 or J-2 for a radiographic test system. The cross-sectional area of one cell is almost double that of J-2. The advantages are obvious since maneuverability of the X-ray components is essential to good overall coverage. Another potential advantage to these locations lies with the state of design for the internal services and engine thrust support. Both items, it is understood, are still being formulated and could easily be designed for the future installation of an X-radiograph system. Planning now for this inspection program would allow maximum coverage of the test article with minimum facility interference later.

In Section 4 "Source Selection," Varian recommends the TELS source as the first choice for use in the turbine engine test cells. Its lightweight, relatively small size, and improved operating characteristics over off-the-shelf equipment clearly makes it the choice for C-1/C-2 as well as J-2. The main drawback to this selection lies in the fact that TELS is a design concept which will require several years to develop and prove in the field. Use of common equipment between the altitude cells and the TELS facility would, of course, be a cost effective approach. However, recognizing that should the TELS equipment not be developed or perhaps delayed in its manufacture, a backup source selection (other than TELS) with its accompanying positioning system for C-1/C-2 would benefit future decisions in this area.

The second selection for C-1/C-2 is the LINATRON 3000 which is a modified L-2000 upgraded in performance to meet the more stringent needs of turbine engine radiography. The size of this machine without an internally shielded accelerator is approximately 72 in. by 29 in. by 28 in.

The first approach was to investigate the leakage shielding needed for the L-3000 at the C-1/C-2 location. With an external vault around the package to attenuate leakage (similar to P&WAs P8 test cell at Middletown, Conn.), the overall weight and size of the assembly is 28,000 lb and 88 in. by 44 in. by 45 in. This is not a desirable approach due mainly to the excessive weight and inherent difficulties in positioning such a load.

The second plan was to have Varian propose an internally shielded package which would not require an external vault. The results were much better in the weight category, i.e., 6,000 lb vs 28,000 lb but only slightly better in size, 80 in. by 40 in. by 40 in.

The first concept, Plan A, for positioning this source and the LMSC detector is shown in figure 38. This design attempted to use an overhead bridge crane type device for moving the source in the axial, radial, vertical, and tilt directions. A hydraulic extension cylinder and motorized yoke assembly provide vertical and tilt movements while air bearings give axial and radial travel. It should be noted, however, that due to the curvature of the chamber wall, the L-3000 cannot be set with a target-to-object distance of more than 60 in. on a 5-ft diameter engine. Relating this to performance data as per table 1, this becomes:

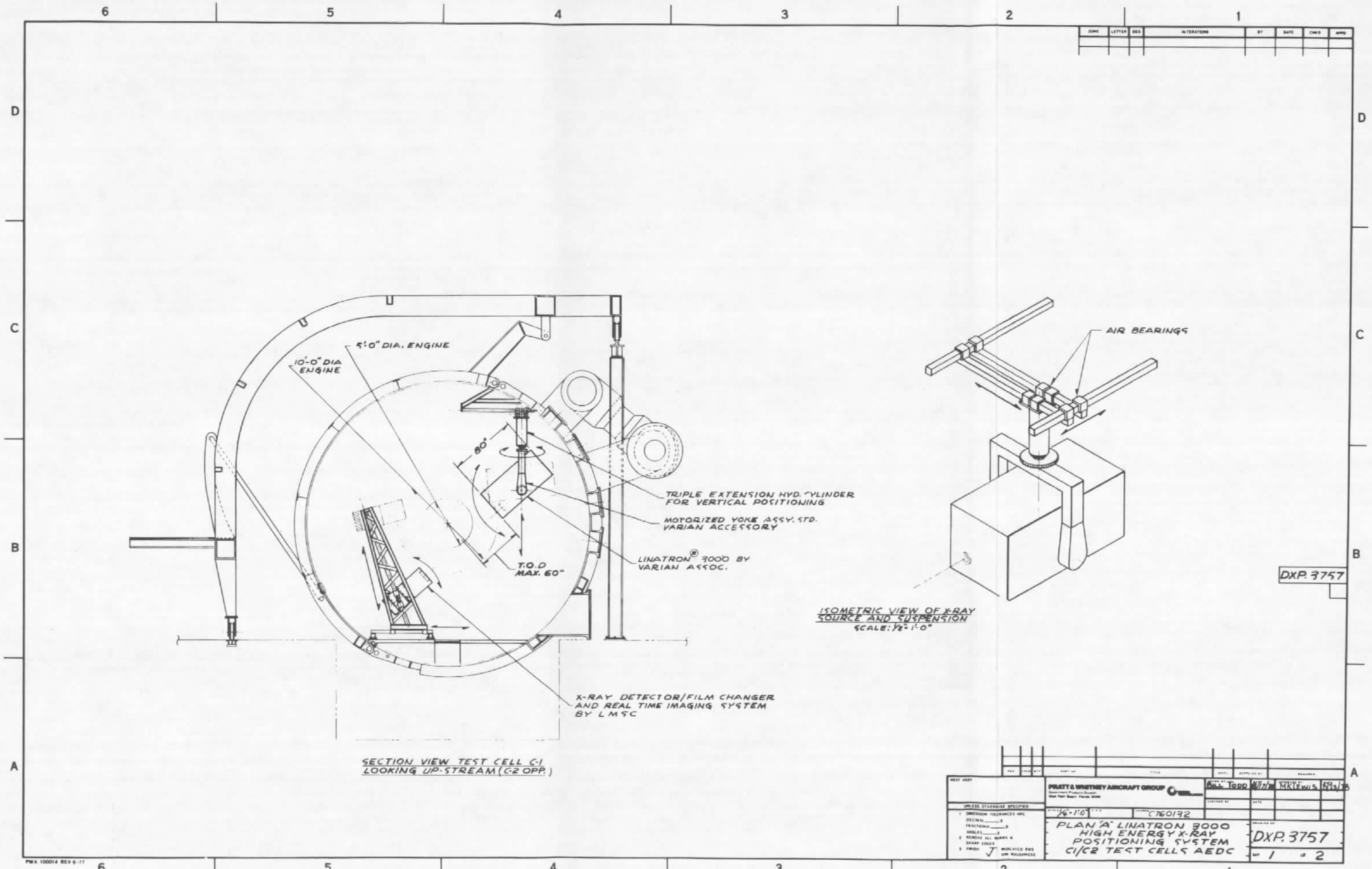
Target-object-distance (TOD), in.	60
Object-film-distance (OFD), in.	36
Geometric unsharpness (U_g)	0.6
Total unsharpness (U_t)	0.73
Exposure time, sec.	1.4

The geometric unsharpness (U_g) is more than the recommended minimum of 0.5 with no capability of reducing this by a larger TOD. For this reason this concept is not considered workable for C-1/C-2.

Plan B, figure 39, shows an alternate approach to positioning the source. It allows for an increased TOD (90 in.) for a 5-ft diameter engine while giving positioning in the vertical, radial, axial, and tilt motions. This sytem gives a U_g of 0.4, well below the 0.5 maximum; however, the exposure time is 2.1 sec, or more than double the minimum 1 sec required.

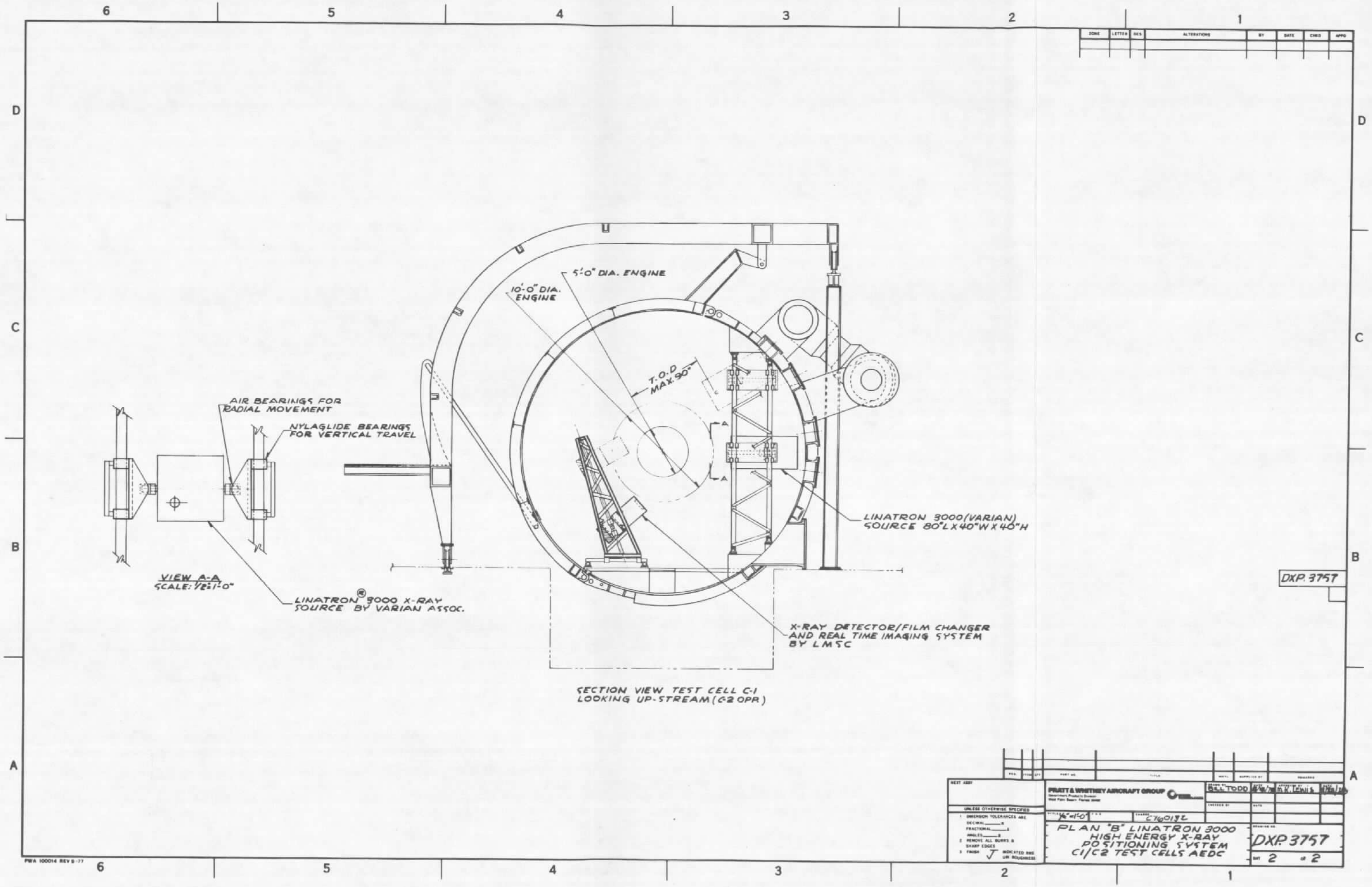
Plans A and B again point out the shortcomings involved in trying to position existing commercial-type radiographic equipment within relatively confined spaces. Although the L-3000 can be mounted and adequately maneuvered within C-1/C-2, the limitations of its positioning place the technical performance of this source in the marginally satisfactory area. This severely restricts its overall potential capabilities.

An additional point not shown in these figures is the longitudinal (axial) coverage required. This would be in the range of 8 to 30 ft depending upon whether compressor-through-turbine or full engine length inspection capability was required. All services, instrumentation, catwalks, etc. must be kept clear of the operating areas of the source and detector.



JXP 3758A

Figure 38. Plan A LINATRON® 3000 Positioning System for C-1/C-2 at AEDC



JXP 3758B

Figure 39. Plan B LINATRON® 3000 Positioning System for C-1/C-2 at AEDC

5.2.4 Test Cell J-5

The J-5 test cell (figure 40) as previously noted is exclusively used for rocket motor testing. Due to the large diameter of strategic rocket motors and the X-ray attenuation characteristics of solid propellants, X-ray sources with high output are required for both static and dynamic X-radiography. In Section 2, it was noted that the only commercial equipment suitable for these purposes is in the LINATRON 6000/RDI Super XX 6000 class. These sources are quite large and cannot be accommodated within the J-5 test cell, thereby requiring a compromise positioning scheme as shown in Figure 41. Basically the system consists of:

- An externally located LINATRON 6000 source positioned by the test cell 20-T bridge crane.
- An internally mounted combination film/electronic imaging device
- An arc shaped fixture which positions the detector in roll, axial, and tilt movements.

Figure 41 depicts the radiography set-up for a 92-in. diameter MX rocket motor. The detector, with its long axis parallel to the motor, is in its normal orientation for most of the required readings, tangential case-bond, forward flap (dome), insulation ablation rates, etc., *except* nozzle throat dynamic inspection. For the latter type set-up it is necessary that the detector be rotated 90 degrees so that the long axis of the casing is downward as shown in figure 42. The ISOCON tube within the detector must be placed with the faceplate *up* to avoid its being damaged by loose photocathode particles in the tube. The 90 degree turn places the film plate across the throat of the motor with the 24-in. dimension of the film fully straddling the 11.5-in. diameter MX nozzle throat.

It will not be possible to utilize the arc positioning mechanism with the detector in this long-axis attitude due to obvious interferences. A special detector support fixture will be required for these nozzle throat readings. The arc positioner can be rolled to the side and the special holder frame bolted to predesigned plates on the floor and wall of the chamber.

In a similar manner the three-detector array of special electronic imaging devices shown in figure 25 can also be mounted to a special rig fastened to the cell. Both of those special set-ups will be fixed in place prior to firing and will not require any repositioning once the chamber is sealed off for firing. These fixtures would be test-peculiar items which would depend on the particular motor being inspected.

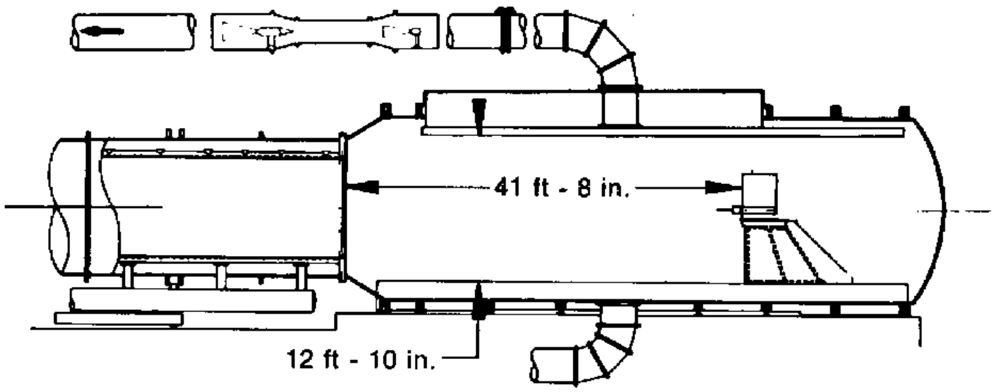
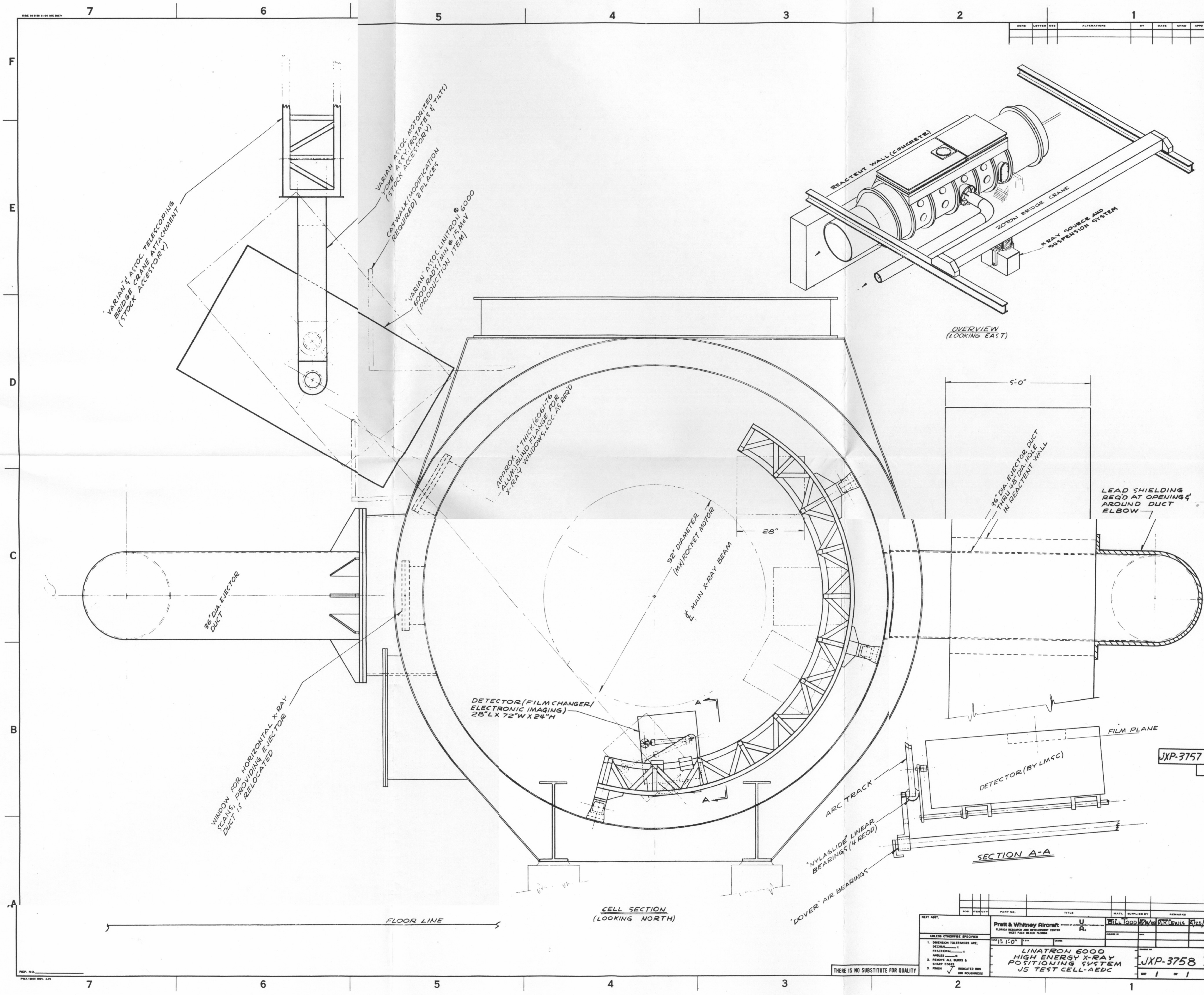


Figure 40. Clearance Volume for Test Article Installation for J-5 Test Cell



JXP 3757

Figure 41. LINATRON® 6000 Positioning System for J-5 at AEDC

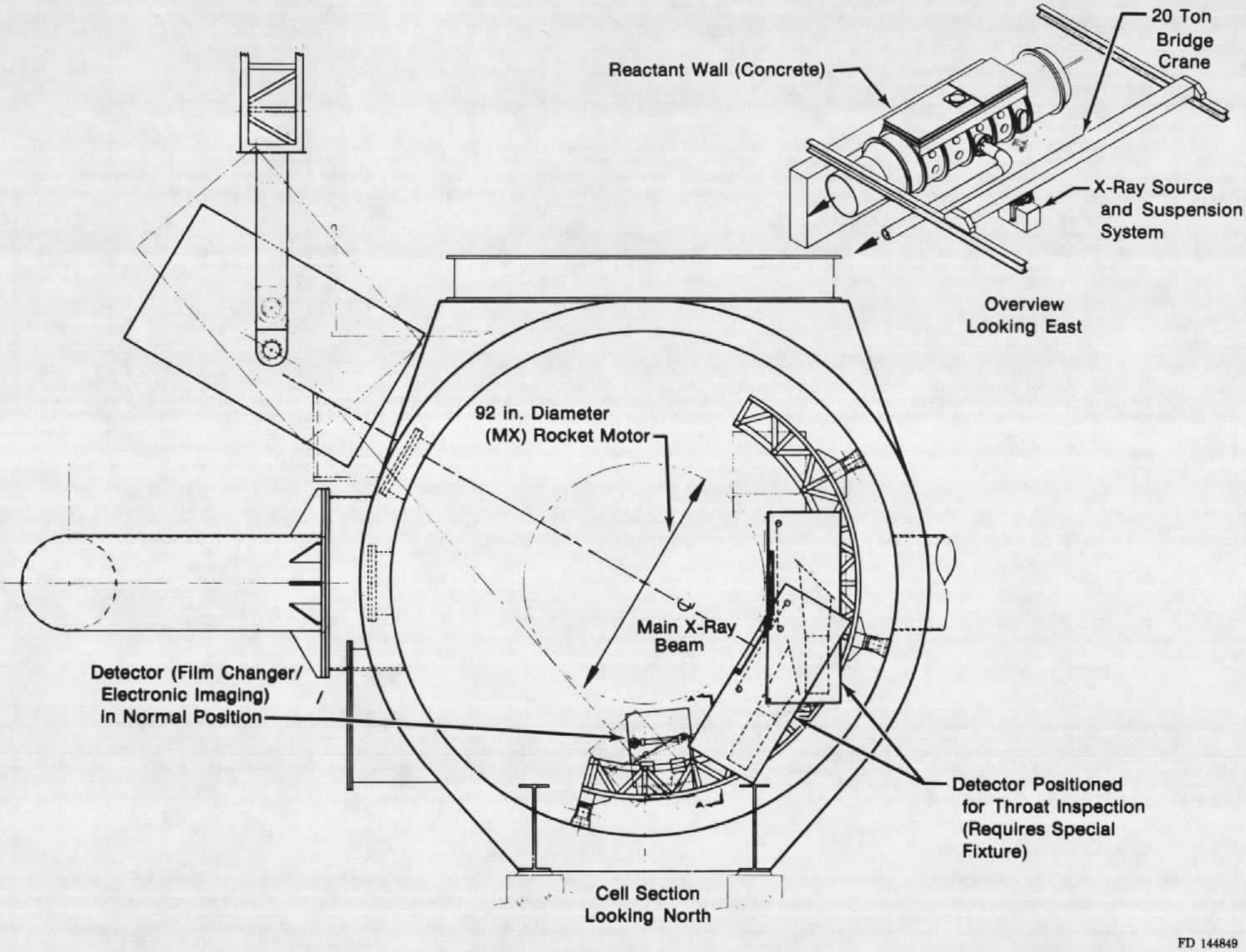


Figure 42. Downward Position of Detector Casing for Throat Dynamic Inspection

It should be noted in figure 41 that two sets of aluminum "windows" through the cell wall are provided for the LINATRON 6000 — one for a 45-degree angle down-shot and one for horizontal readings. The upper window will be normally used; however, the horizontal window is essential for added flexibility to the overall radiography program at this stand. The 36-in. diameter ejector duct on the west side of the chamber will require modification in order to provide sufficient clearance for the LINATRON 6000 to drop down to this horizontal position. For the 45-degree position, both catwalks on this side will require relocating.

A typical final assembly for the LINATRON 6000 with its power and services is shown in figure 43. The power modulator will probably require mounting somewhere midway between the J-5 control room and the LINATRON 6000 X-ray head in order to satisfy the maximum cable lengths shown. Figure 44 shows the probable location of the modulator for this installation.

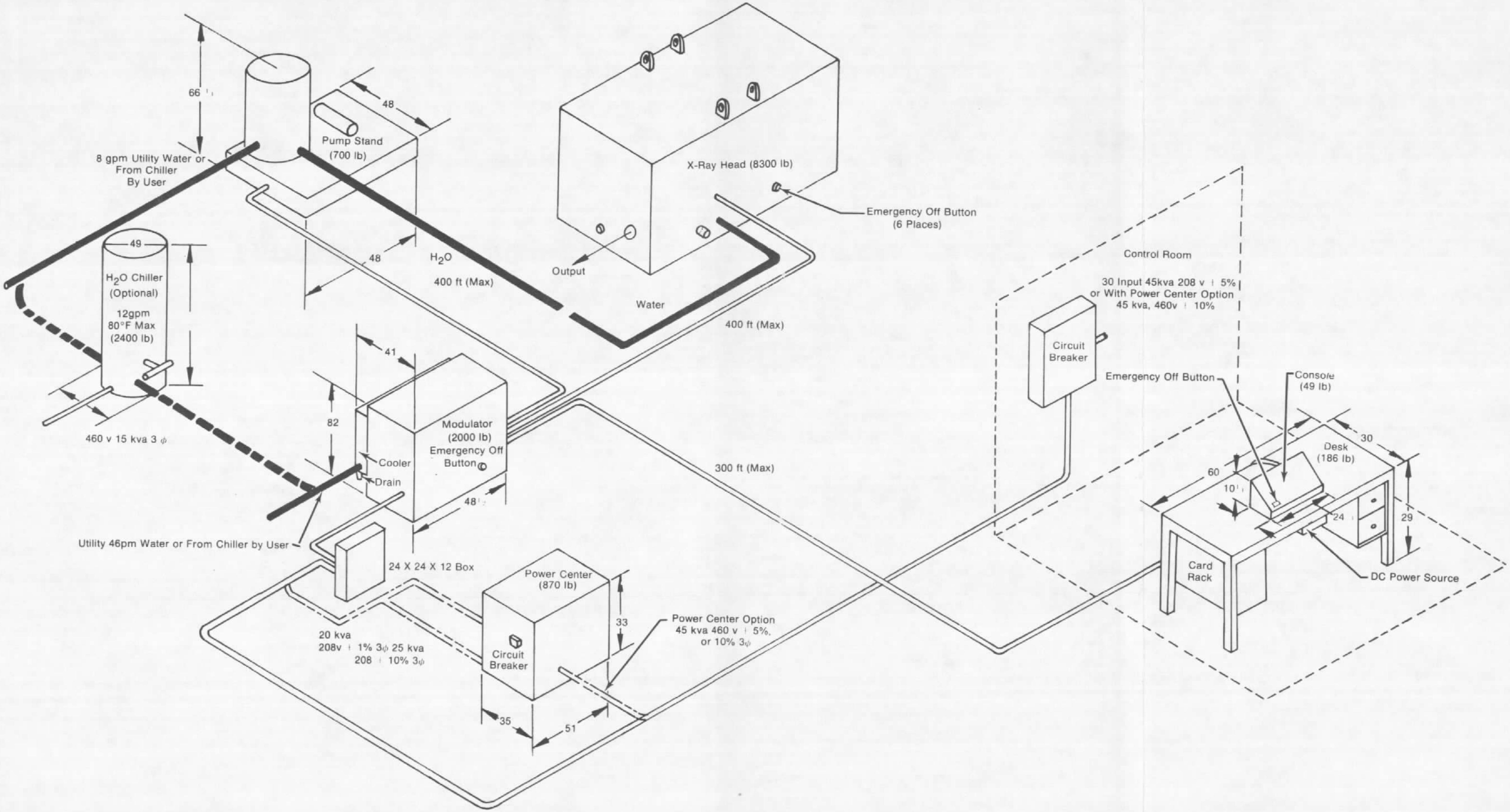


Figure 43. LINATRON® 6000 Final Assembly

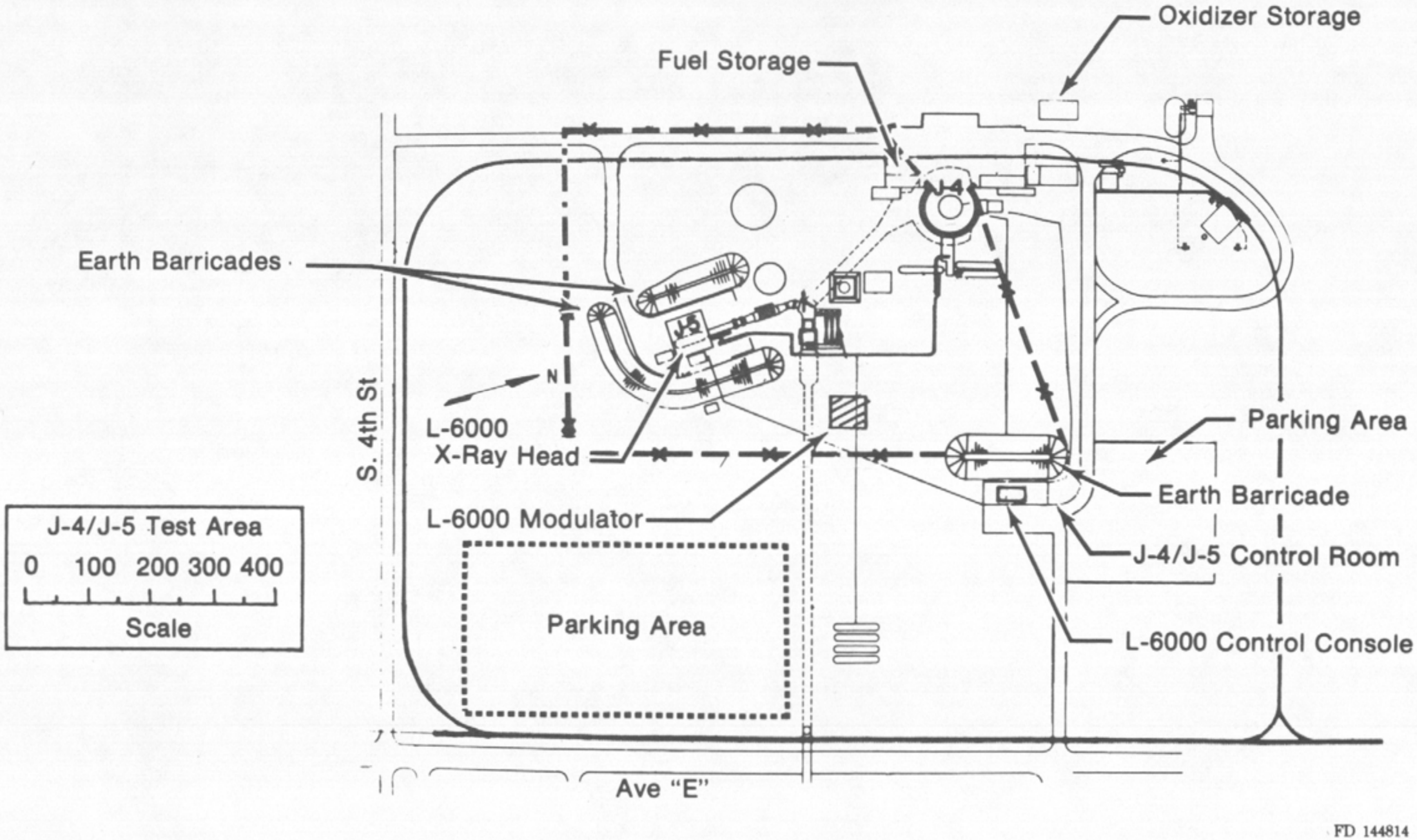


Figure 44. LINATRON® 6000 Installation Scheme for J-5

SECTION 6
AFFECTS OF ALTITUDE CELLS ON IMAGE QUALITY

6.0 SCATTER RADIATION

Of the various items that affect X-radiographic image quality in turbine engine radiography, the one that produces a significant difference when comparing various engine test cells is scatter radiation. In order to evaluate the affect of the test cell geometry and materials on the image quality, we considered the ways in which these items affected the quantity of scatter radiation at the detector and compared this to what was predicted for testing in a typical sea level engine radiographic facility. These comparisons and experience with the quality of X-radiographic images obtained under sea level conditions, were used to predict the effect on image quality due to the altitude test cell environment.

Scatter radiation is secondary radiation generated by the interaction of the primary X-ray beam with material along its path. Material items that intercept the radiation initially dispersed from the "primary" sources of the scatter will be considered as "secondary" sources of scatter radiation. For high energy radiation, scatter accounts for a large portion of the primary beam attenuation.

The scatter radiation in X-radiographic exposure is generally a significant portion of the total radiation incident upon the detector. The primary effect of the scatter radiation is to reduce image contrast resulting in decreased thickness sensitivity and an increase in the minimum discernible clearance.

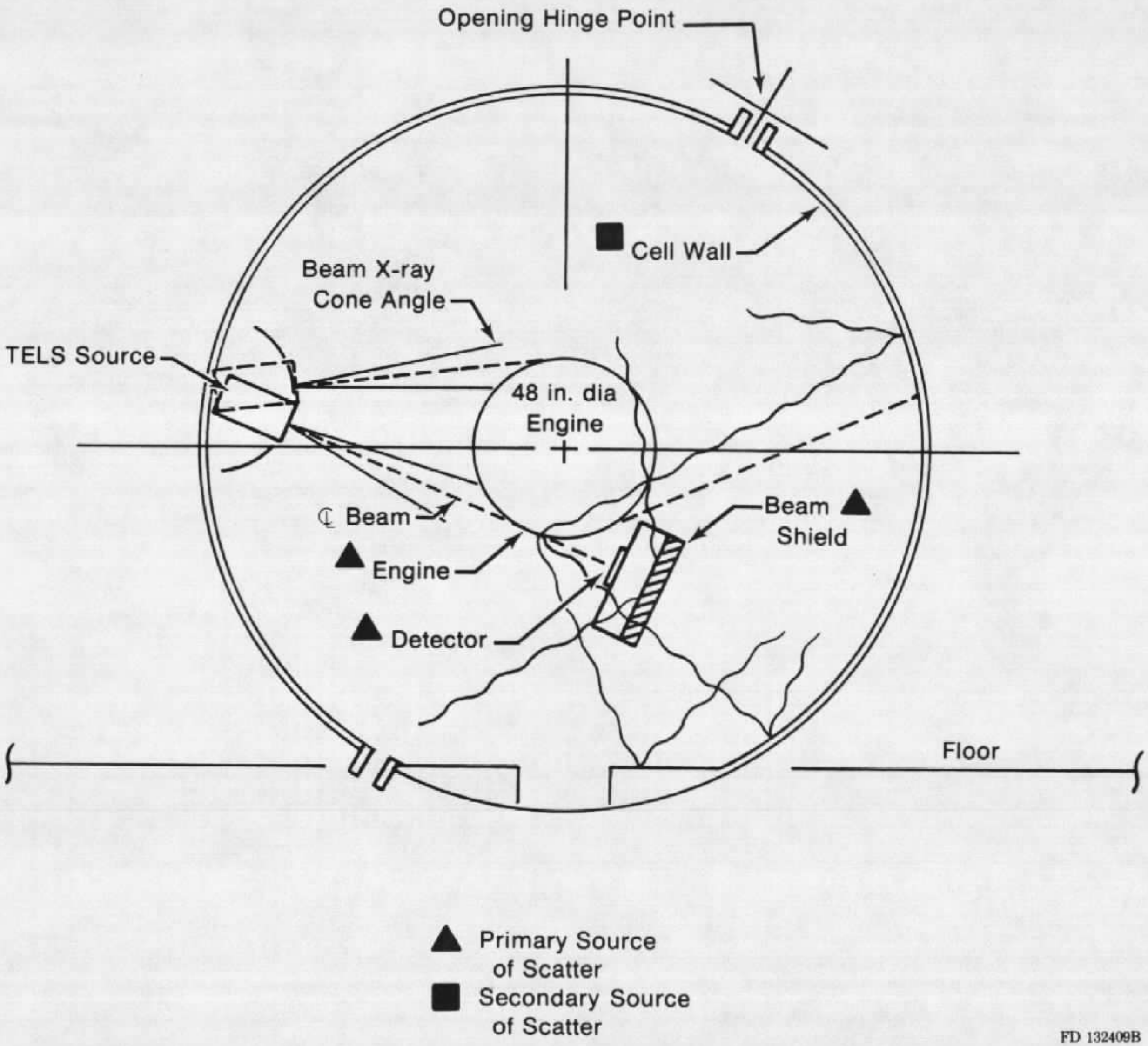
6.1 FACTORS AFFECTING RADIOGRAPHIC QUALITY

There are two basic concepts for X-radiographic measurements in the altitude test chambers that concern radiographic quality:

1. X-ray source inside the test chamber (figure 45)

2. X-ray source outside the test chamber (figure 46).

Each of these concepts affect the scatter X-radiation reaching the detector.



FD 132409B

Figure 45. Test Cell Source Mounted Internally and Radiation Scatter Patterns

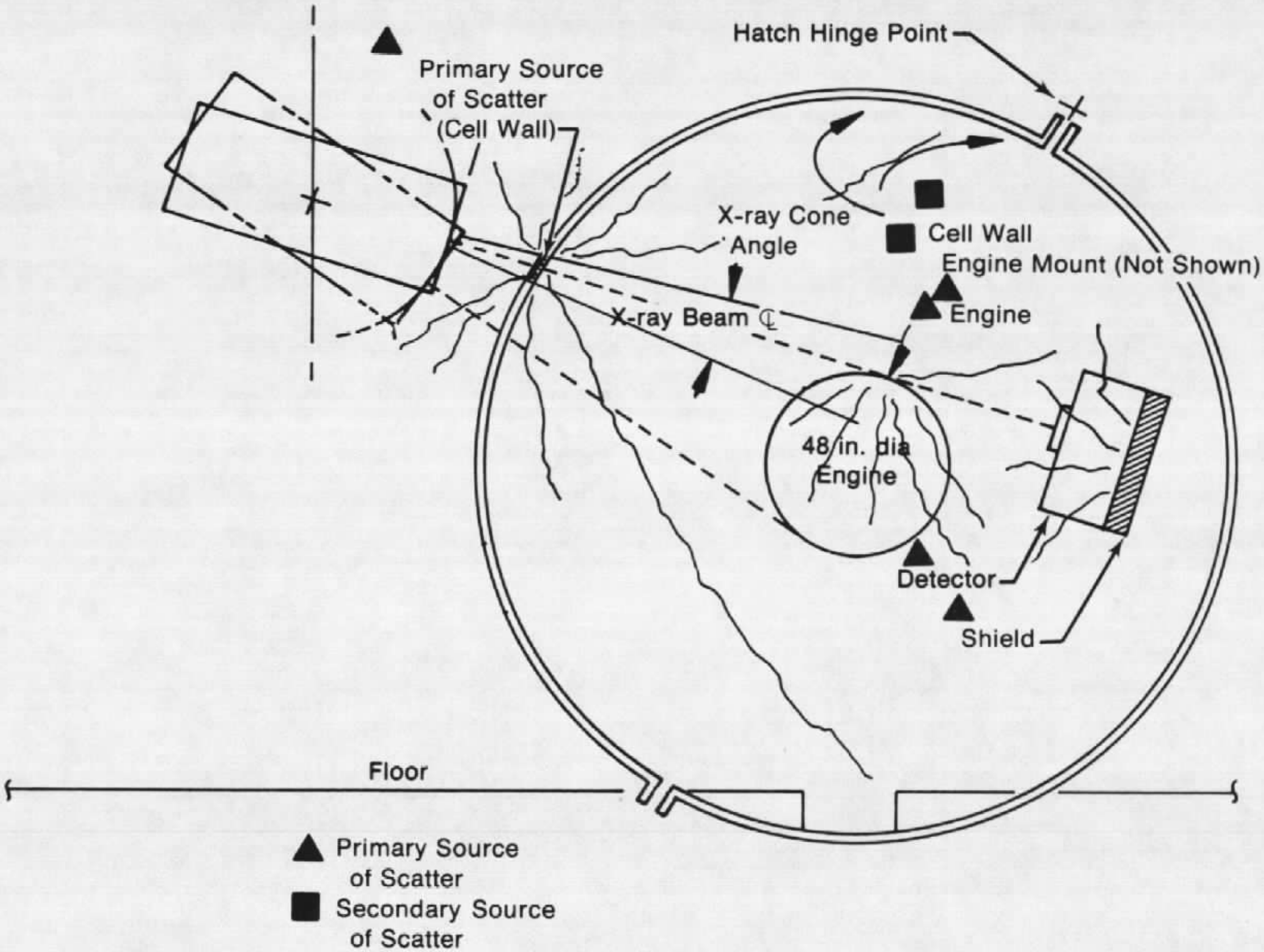


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Figure 46. Test Cell Showing Source Mounted Externally and Radiation Scatter Patterns

In Concept 1, the X-ray source is contained within the chamber. The "primary" sources of scatter are the engine, detector system, and the backscatter/primary beam shield (figure 45). The secondary sources of scatter radiation are the test cell walls, the engine mount, and other items within the chamber. This geometry is similar to that encountered in the P&WA JT9D sea level test facility at Middletown, Connecticut. The major differences are the material of the secondary sources and the proximity of the sources to the detector. The materials are concrete for the sea level test cell and steel walls for the altitude cells. Given two test chambers of circular cross section of the same material with the same primary scatter sources, but differing in diameter, both will realize the same total scatter radiation. However, the smaller diameter chamber will deliver more scatter radiation at a higher energy to the detector than will the large diameter chamber. This results in an increase in the ratio of scatter to primary radiation. This is due primarily to the presence of more scatter radiation at the detector, and because techniques that might be used to control scatter do not generally operate as effectively at high energies as they do at low energies. Without a quantitative estimate of the image degradation, we can say that test cells J-1 and J-5, which are 16 ft in diameter, will produce a poorer radiograph than the J-2 test cell which is 20 ft in diameter. All are likely to give results poorer than can be obtained in a 24-ft diameter sea level test facility. This conclusion is based only on dimensional characteristics.

In Concept 2, the X-ray source is located outside the test chamber. The primary difference from Concept 1, in which the X-ray source is inside the chamber, is the introduction of another primary scatter source (Figure 46). This is located at the point of intersection of the primary beam and the test cell wall. The size of the scatter source depends upon the X-ray beam total cone angle and the distance between the X-ray source and the test cell wall. A preliminary look at typical geometries for Concept 2 indicates that the scatter source represented by this intersection point can be considered, for the purposes of analysis, as a point source of scatter radiation. Because the engine is generally between this primary source and the detector, the major contribution to the total scatter will be scatter from the secondary sources generated by this additional scatter source. These secondary sources will be the test cell wall at points other than where the primary beam intersects it. The high energy nature of the low angle scatter from the wall source of primary scatter makes it exceedingly difficult to shield the detector from this radiation. The high energy of this low angle scatter penetrates the engine as easily as the radiation from the X-ray source itself. The image formed by the primary wall source will be very blurred and underexposed. The result of this blurred image is a decrease in contrast of the primary radiographic image. Regarding image quality, it is obvious that elimination of this additional source of scatter would be advantageous. If Concept 2 is utilized, it would be useful to provide a window at the test cell wall fabricated from a low attenuation coefficient material. This

window could be glass, fiberglass, aluminum, or some other suitable material. The best material would have to be determined by first considering the thickness of the material required for structural purposes. The material's attenuation coefficient would determine the attenuation of the primary beam and the amount of scatter produced. The material giving the best compromise between attenuation, scatter, and structural integrity would be the best choice for a window material. Even with a low attenuation material, the scatter radiation expected at the detector would be greater than that expected in Concept 1.

6.2 QUANTITY OF SCATTER RADIATION

The primary difference between Concepts 1 and 2 and sea level radiographic test cells, assuming the same radiographic geometry, is the quantity of scatter radiation in the plane of the detector resulting from the distance of the test cell walls from the detector, the wall material differences, and the wall thickness.

A look at the geometry involved indicates that the "scatter-of-importance" in determining the differences between altitude and sea level radiographic images are the secondary sources which are, by their definition, usually less important than primary scatter sources. The energy from the secondary sources that is peculiar to the altitude test cell and which affects imagery is below 0.5 MeV. At this level of energy, the scatter generated is roughly proportional to the difference between the incident and the attenuated beam intensities. Radiation that leaves the scatter source is a function of the angle, distance traveled, and the attenuation coefficient of the scatterer.

6.2.1 Scatter Radiation as a Function of Cell Materials

The material of the chamber walls of a test cell influences the amount of scatter available. The material of the AEDC altitude test cells is steel of about 2-in. thickness. The radii of the altitude test cells are 8, 10, and 14 ft. This is in contrast to concrete walls 3- to 8-ft thick and an equivalent radius of about 12 ft for the P&WA 8-MeV X-ray facility.

Since the wall thickness of the AEDC altitude test cells and the concrete walls in the P&WA sea level facility are about two mean freepaths thick for the radiation in question, the thickness does not play an important role in the comparison of the effects of scatter between the cells. Consequently, the major parameters to be evaluated are the wall material and test cell diameter.

It can be shown[14] that the X-ray energy flux in a room of any shape from a point source at the center is constant and isotropic if the radiation escaping from the walls has an angular

distribution which is nearly cosine shaped. Also, in general, it is sufficient to include only first scatter from the walls. The X-ray energy flux, ϕ_e, is given by:

$$\phi_{e1} = A_{Je}/\pi R^2$$

where A_{Je} is the energy current albedo of the cell and R is the radius of the cell. A_{Je} is the ratio of the energy scattered from the wall to the energy incident on the wall.

As a first approximation, we can consider the portion of the engine scattering the primary beam as a point source. Since the scatter from the engine is not isotropic, our assumed point source is not isotropic. However, for the purpose of evaluating the effect of radius and wall material on scatter radiation reaching the film for the various test cells, it is felt that the above equation will be suitable.

If we wish to compare two test cells of the same diameter, we can use the above equation and write:

$$\frac{\phi_{e1a}}{\phi_{e1b}} = \frac{A_{Jea}}{A_{Jeb}} = \beta$$

where the subscript a refers to one material and b to the other material.

The values of A_{Je}[14] are for monochromatic radiation. Since the radiation in the test cell is not monochromatic, the ratio in the second equation was calculated for energies to 0.5 MeV and averaged. These should be weighted averages. However, the weights would be the same for any wall material and are not easily determined; therefore, a weight of one was assigned to each β calculated.

The concrete and steel walls were compared to a lead wall. Lead walls would be expected to produce less scatter than either the steel or concrete. In comparing concrete and steel, the energy flux of the steel was found to be 0.41 times the energy flux of the concrete. Comparing concrete and lead, the energy flux of the lead cell was approximately 0.05 times the flux of the concrete. Lead versus steel gave the flux of lead to be 0.12 times the flux of steel. Therefore, given three test cells of the same diameter of concrete, steel, and lead, the lead cell would realize only 5% of the scatter energy flux of concrete and the steel only 41% that of concrete. *This means that scatter in test cells C-1 and C-2 would be less than that experienced in existing sea level facilities.*

Test cells J-1, J-2, and J-5 are all smaller in diameter than the X-ray facility at P&WA. The first equation was utilized to evaluate the effect of this reduced diameter on image quality. Test cells J-2 and J-5 were found to have more scatter by a factor of 6 than the P&WA facility.

Since the albedo is defined as the ratio of scatter to incident flux, we have only about 8 to 10% of the total flux scattered from the engine reaching the cell walls and only 0.08% of that flux is returning to the film plane. If the engine scattered the entire 2000 rad/min emitted by the source, only 0.18 rad/min would be available at the film plane from backscatter from the walls in J-2. Since most exposures only take about 10 sec and represent about 1.5 rad at the film plane, approximately 2% of the exposure would be due to the wall backscatter for the case of J-2 compared to 0.4% for a 12-ft concrete test cell.

The scatter at the film plane that comes directly from the engine is in the neighborhood of 80% of the direct, image-carrying radiation. For 1.5 rad at the film plane, 0.83 rad will be image-carrying information and 0.67 rad would be due to engine scatter. For the J-2 example, the scatter from the wall would increase this to about 0.70 rad, while for the concrete test cell (12-ft dia) the wall scatter would increase the total scatter to 0.68 rad. Therefore, the scatter at the detector due to scatter from the walls of J-2 is approximately 4.3% of the total scatter while the contribution of the concrete walls is 1.5% of the total scatter.

While these numbers are only approximations to the actual physical situation, it is felt that the trends indicated are valid.The scatter from the walls of the altitude test cells at AEDC will not significantly affect the quality of the radiographic image. These results are valid for Concepts 1 and 2.

In Concept 2, the additional scatter present due to the penetration of the X-rays through the test cell walls will be proportional to the buildup factor of the wall material. In comparing two materials of the same thickness, the ratio of the buildup factors would be indicative of the ratio of the scatter from the two materials at the film plane.

6.2.2 Effects of "Window" Materials

We are interested in the effect of a specific "window" material that might be installed in the steel walls of the altitude test cells on the scatter at the film. Comparing equal thicknesses of steel and aluminum, we find that aluminum creates only 86% of the scatter of steel. In addition, more direct radiation is available at the film, thereby reducing exposure time. Experimental data obtained at P&WA on the effects of scatter from 2 in. of concrete (located in the X-ray beam near the source) on image contrast, indicated that 6% loss of image contrast could be realized. Since aluminum and concrete have similar scatter properties, the same effect would be expected. This does not appear to be a substantial problem for engine radiography where there is high subject contrast. The primary objection to Concept 2 would be the increased exposure time rather than scatter radiation on the image.

The scatter radiation that exists in an altitude test cell can be controlled to a certain extent by a variety of techniques. One that is useful for imagery, as well as health and safety, is the reduction of primary beam size. Another technique is to use lead filters and intensifying screens or lead-back screens. The effects of radiation from secondary scatter sources can also be reduced by using side shields on the detector system.

In summary:

1. A minor loss of radiographic contrast will be realized in test cells J-1, J-2, and J-5 as compared to existing sea level test facilities.

2. Test cells C-1 and C-2 will provide superior radiographs to those obtained at existing sea level cells.

3. The advantages of Concept 1 over Concept 2 are:

   - Shorter exposure time
   - Higher radiographic contrast.

SECTION 7
REVIEW/CONCLUSIONS

7.0 GENERAL

The objective of this contract as stated previously was to study the feasibility of installing an X-ray inspection system in various AEDC altitude test cells. The major tasks involved were: *Source Selection, Detector Conceptual Design,* the determination of a *Positioning Concept* for each viable test location and *operational safety.*

The resultant ideas, concepts, considerations, and conclusions as determined by P&WA, Lockheed, and Varian in each of these major areas are briefly reviewed in this section.

7.1 Source Selection — General

The source selection process evolved into four principle steps:

- Establishment of design criteria
- Selection of candidate sources for consideration
- Study of source technical capability versus design requirements.
- Analyses of comparative data in conjunction with other influencing factors such as:
  - — Radiation safety
  - — Cell modifications required
  - — Positioning flexibility
  - — Cost
  - — Image quality.

7.1.1 Candidate Sources

The major candidate sources considered were:

<u>*Varian, Inc.*</u>	<u>*Radiation Dynamics, Inc.*</u>	<u>*Mitsubishi*</u>	<u>*TELS*</u>
* • L-2000	• Super XX	* • ML 15R	• Standard Model with Internal Shielding
• L-3000 with Internal Shield			• Modified Model (Repackaged)
* • L-6000			

(*Existing Off-the-Shelf Equipment)

7.1.2 Source Parameters

The significant technical parameters of the sources selected for study are shown in table 9.

A tabulation of comparative data showing source capability versus design criteria is shown in tables 10 and 11.

TABLE 9. SOURCE PARAMETERS

X-Ray Source	L-2000	L-3000	L-6000	TELS with Internal Shield	Super XX	ML 15R
Electron Beam Energy, MeV	8	10	15	8	12	12
Output, rads/min at 1m	2000	3000	6000	3000	6000	3000
Source Diameter, mm*	1.0	1.0	1.0	1.0	1.0	1.0
Overall Length, in.	66	80	99	48	56	123
Height by Width, in.	29 by 28	40 by 40	60 by 62	32 by 24	124	34 by 28
Weight, lb	2000	6000	8300	2400	6600 with pretzel	6600

* Arbitrarily fixed at 1.0 mm for all machines, capability not established in all areas.

TABLE 10. TURBINE ENGINE GENERAL X-RAY SOURCE REQUIREMENTS VS CAPABILITIES

	Spectrum Photons to 8 to 10 MeV	Flux ≥50 rad per sec at 1m	Shape Circular	Diameter 1.0 mm	Pulse Width 2 to 5 μsec	Pulse Rate 50 to 350/sec (adj)	Field Angle 8 to 1 deg Total Cone Angle (adj)
L-2000	X	No	X	X	X	X	X
L-3000	X	X	X	X	X	X	X
L-6000	X	X	X	X	X	No	X
Super XX	X	X	No	X	X	Unknown	X
ML 15R	X	X	Unknown	X	X	Unknown	X
TELS	X	X	X	X	X	X	X

X — Acceptable

TABLE 11. ROCKET ENGINE GENERAL X-RAY SOURCE REQUIREMENTS VS CAPABILITIES

	Spectrum Photons to 12 to 15 MeV	Flux ≥100 rad per sec at 1m	Shape Circular	Diameter 1.0 mm	Pulse Width 2 to 5 μsec	Pulse Rate 50 to 350/sec	Field Angle 15 to 20 deg Total Cone Angle
L-2000	No	No	X	X	X	X	X
L-3000	No	No	X	X	X	X	X
L-6000	X	X	X	X	X	X	X
Super XX	X	X	No	X	X	X	X
ML 15R	X	No	Unknown	X	X	X	X
TELS	No	No	X	X	X	X	X

X — Acceptable

7.1.3 Source Selection — General Conclusions

Considering all major influencing factors, the following key items in overall source selection were established:

1. The L-6000 or Super XX are the most suitable X-ray units for rocket engine testing.

2. The L-6000 most closely meets the general X-ray performance requirements for *both* turbine and rocket engines.

3. The L-6000 is not however, suitable for turbine engine testing in J-2, C-1 and C-2 because:

    - Large personnel exclusion radius is required (400 to 600 ft)

        — To reduce to 100 ft radius would require lead vault of approximately 22,000 lb

        — To reduce to 50 ft radius would require lead vault of approximately 44,000 lb

    - Positioning flexibility is too restricted

    - Free jet testing would be hindered with this large piece of equipment inside the cell

    - Image quality is reduced below minimum requirements.

4. The Super XX and ML 15R X-ray sources are not suitable for the turbine engine cells for reasons similar to those for the L-6000.

5. Rocket and turbine engine testing at AEDC require *two* distinct sources:

    - L-6000 or Super XX for rocket testing

    - L-2000, L-3000, or TELS for turbine testing.

6. None of the candidate sources are entirely suited for the J-1 test cell due to:

- Inadequate positioning room inside the chamber
- Extensive cell modifications required to provide positioning space
- Unsatisfactory radiographic performance of most sources at this location (Section 5)
- Excessive radiation scatter within work area for outside location of sources.

With a clear distinction between the rocket and turbine engine testing needs as well as the obvious division of X-ray units suitable for these programs, an evaluation of these equipment options for each test location (J-1 excepted) is provided in the following paragraphs.

7.2 Source Options for J-2 Application

Extracting data from table 2, page 41 and incorporating them into table 12, a comparison can be drawn of source radiographic performances for the L-2000, L-3000, and TELS for the J-2 position.

TABLE 12. COMPARISON OF X-RAY SOURCE FOR TEST CELL J-2

Parameter	*L-2000*			*L-3000*			*TELS*		
	Inside (Max)	*Bubble* (Opt)	*Outside* (Min)	*Inside* (Max)	*Bubble* (Opt)	*Outside* (Min)	*Inside* (Max)	*Bubble* (Opt)	*Outside* (Min)
Source-Engine Distance, in.	51	88	132	45	78	140	75	88	132
Source-Film Distance, in.	87	124	168	81	114	176	111	124	168
Geometric Unsharpness, mm	0.7	0.41	0.3	0.8	0.47	0.3	0.5	0.41	0.3
Total Unsharpness, mm	0.8	0.62	0.6	0.9	0.68	0.6	0.7	0.62	0.6
Exposure Time, sec	1.7	3.5	10.5	0.9	1.8	7.0	1.8	2.3	6.9
Bubble Radius, ft		13.6			13.7			11.6	

Opt = Optimum

7.2.1 LINATRON 2000 (J-2)

An evaluation of the facts concerning the LINATRON 2000 at J-2 is outlined in table 13 From this, it was established that:

- The L-2000 can be used at J-2 under the "bubble" concept but is not recommended for this application because of:
  - — Marginal measurement capabilities
  - — Extensive modifications required for the chamber
  - — Extensive shielding needed for leakage radiation protection coupled with a large exclusion radius.

TABLE 13. EVALUATION OF L-2000 FOR J-2 APPLICATION

	Inside	*Bubble*	*Outside*
Problems	• Leakage radiation requires exlusion radius of ~250 ft —lead vault >7,500 lb (~78 ft) - decreased positioning flexibility —Internal shielding of L-2000 - X-ray source no longer off-shelf - ~100% of cost increase • Restricted measurement capability —large unsharpness • Restricted positioning —no room to move	• Leakage radiation is same as "inside" • Exposure times long • Extensive test cell modifications	• Leakage radiation • Additional scatter radiation • Cell modifications • Excessive exposure time
Advantage	• Off-shelf system • Shields scatter and leakage radiation	• Off-the-shelf source • Good image quality • Shields scatter and leakage radiation	• Same as bubble

7.2.2 LINATRON 3000 (J-2)

The LINATRON 3000 provides fairly adequate radiographic capabilities at J-2 under the "bubble" concept, but is not recommended for this application because:

- The source is not off-the-shelf
- Extensive shielding will be required, as well as a large personnel exclusion radius (250 ft)

- Large modifications will be required for the chamber

- Unit is bulky and heavy thereby limiting the positioning flexibility.

7.2.3 TELS Standard (J-2)

As evaluated, this equipment performs satisfactorily either inside the cell or with the "bubble."

The TELS source positioned inside the chamber is the best choice because:

- It provides adequate measurement capabilities
- No extensive test cell modifications are required
- No vault is required to reduce leakage radiation
- X-ray source weight (2400 ℔) relatively easy to position
- It will be common with the TELS facility.

The disadvantages are:

- Currently not available and will require long-lead development time

- Greater cost than L-2000 and L-3000.

7.3 Source Options for C-1/C-2

7.3.1 LINATRON 2000

The LINATRON 2000 as applied to C-1/C-2 can be evaluated the same as previously shown in table 13 for J-2.

The equipment *is not* considered suitable inside C-1/C-2 because of the marginal measurement capabilities and the large shielding vault needed at this location.

7.3.2 TELS Standard

The TELS system provided excellent performance within the chamber, and no modifications to the cell are necessary for positioning.

The TELS system is the recommended *first choice* for C-1/C-2 in accordance with those advantages and disadvantages listed previously (paragraph 7.2.3) for J-2.

7.3.3 LINATRON 3000

This source with its internal shield is capable of performing adequately and could be utilized as *a backup choice* for C-1/C-2. Although it is not generally considered off-the-shelf equipment, the basic components will evolve from an existing proven X-ray unit, the L-2000. Positioning within C-1/C-2 appears marginal, but is better than a vaulted L-2000.

7.4 Source Options for Test Cell J-5

The L-6000 and Super XX are suitable for this location. The *L-6000 source is recommended* over the Super XX for the J-5 application because:

- The 15 MeV spectrum delivers more radiation to the detector than the 12 MeV spectrum of the Super XX.

- The Super XX with pretzel magnet may not give a circular source

- No production model of the Super XX has been released to date.

7.5 Detector Options for J-2, C-1/C-2, and J-5

As described in Section 4, one detector can be developed for use in both turbine engine cells (J-2 and C-1/C-2) and the rocket engine cell (J-5). The unit will measure 72 by 24 by 28 in. and weigh approximately 1800 lb. It will contain a film changing unit capable of recording an image size of 12 by 24 in. and an electronic imaging device (isocon camera) with an image size of 12 by 12 in. An optional detector (figure 24) with only electronic imaging and a view field of 12 by 16 in. has been proposed for J-5. This unit would be used in a set of three, arrayed around the motor (figure 25) to observe the propagation of the flame front over a large fraction of the burn duration.

7.6 Positioning Systems

In general, the existing cells J-2 and J-5 afford very limited space for positioning X-ray equipment. The smaller J-1 test cell precludes all possibilities of adequate positioning.

7.6.1 J-2 Test Cell

Positioning of the source and detector within this cell is feasible, but will require an extremely close fit of all components. The positioning device (figure 36) is arc-shaped in order to fit closely within the chamber walls. All degrees of freedom are attainable for movement of the X-ray components. Existing cabling, piping, catwalks, etc., (Appendix C, figure C-7) must be

relocated to clear the field of operation around the test article. All engine special test supports should be carefully designed or modified to provide maximum circumferential viewing for the X-ray source.

7.6.2 C-1/C-2 Test Cells

These cells offer the best positioning flexibility for inside-the-chamber installations. Their large diameters (28 ft) afford a relatively spacious area (as compared with J-2 and J-5) in which to operate. Again careful attention will be required of the positioning device design in order to integrate the X-ray system into the chamber. Plans A and B (figures 39 and 40) show the L-3000 positioning system using more conventional components than that of J-2.

7.6.3 J-5 Test Cell

Due to the small diameter here (16 ft) internal positioning of a source is impossible. Fortunately the larger more powerful X-ray unit (L-6000) required for the rocket inspection will operate satisfactorily outside of the chamber. The existing 20-T bridge crane can be modified to provide proper positioning capabilities for the source. Coverage of the rocket motor by the source will be restricted to the west side of the cell because of the large 5-ft thick concrete barrier on the east side. This presents no significant problem; however, the exhaust duct shown in figure 41 must be extended further away from the chamber in order to allow the L-6000 clearance for horizontal X-ray shots. Forty-five degree shots downward into the test article appear to be clear with the exception of existing catwalks which can be easily relocated.

7.7 Operational Safety and Shielding

All positions, J-2, C-1/C-2, and J-5, are capable of being adequately shielded for personnel safety. All systems will use a combination of source internal shielding, external primary beam shielding (concrete walls) and reasonable personnel exclusion areas during operation.

7.7.1 J-2 Test Cell

The essential features here are:

- Control room occupation acceptable during testing, but with restricted points of access

- Source (TELS) accelerator shielded for leakage radiation (figure 14)

- External concrete barriers and personnel exclusion areas required (figure 17).

7.7.2 C-1/C-2 Test Cells

The safety features here are:

- The Data Conditioning Room (DCR) (second floor above Mechanical Equipment Room) will be a radiation-controlled area

- The Control Room (second floor, east of DCR) will be an uncontrolled area

- The source accelerator (either TELS or the L-3000) will require shielding

- External concrete barriers and a personnel exclusion area will be needed (figure 18).

7.7.3 J-5 Test Cell

J-5 offers the best existing shielding of all locations. Figure 15 shows the earth barriers now located around the cell. Figure 16 gives the elevation view of the 5-ft thick wall behind the cell. In summary:

- Unrestricted access to the control room during operation

- No added shielding needed for the L-6000 source

- No additional concrete barriers required

- A personnel exclusion fence will be necessary (figure 15).

SECTION 8
RECOMMENDATIONS

8.0 GENERAL

The results of this study indicate that effective diagnostic X-ray systems for both the turbine engine altitude cells J-2 and C-1/C-2, and the solid propellant rocket motor stand J-5 are attainable within the specified operating parameters. Key facts established by this report show that:

- Use of *existing* production-type X-ray units for the *turbine engine stands* requires extensive cell chamber modification.
- Use of a *TELS-type* compact source for the *turbine engine stands* does not require any chamber wall modifications.
- The *rocket engine* radiography for J-5 can be accomplished with a high energy type source now available within the industry. Further source development for this program is not necessary.
- No single imaging system exists which is capable of meeting the special needs of the altitude testing program. Development of a tailor-made detector as discussed in Section 4 will be required.
- Personnel safety and radiation protection are economically possible at J-2, C-1/C-2, and J-5.
- Complete system survivability under test engine failure conditions is not possible where a component is located within the chamber. Partial hardening of the equipment can be provided.
- Portability of complete systems between cells is not possible. The only component items meeting this criteria are the X-ray detector, and the TELS source. (See 8.1.5.)
- The effects of the altitude test cell environment on the quality of radiographic clearance measurements are minimum.
- Positioning flexibility of the X-ray components is very limited at J-2 and J-5. C-1 and C-2 provide fairly good flexibility, but are not ideal.

8.1 Recommendations

8.1.1 J-1 Test Stand

This is not a viable test location for a diagnostic X-ray system and should not be further considered. Available space precludes adequate positioning of the components for effective radiography.

8.1.2 Test Cells C-1/C-2

These are considered the most promising test locations for turbine engine X-ray inspection and are strongly recommended for further study and development. The advantages are:

- Relatively large chamber space for inside mounting and positioning of all components.

- These to-be-constructed stands could be adapted to a future X-ray system by incorporating design changes now rather than by costly hardware revisions after the stands are put into operation.

- High performance engines as well as transport engines can be tested.

- Radiographic results are better than those provided at J-2.

- Radiation protection measures are easier to incorporate here than at J-2.

8.1.3 Test Cell J-2

This position is the second choice for turbine engine testing. Internal space available, flexibility of positioning, and ease of incorporating safety protection fall below those capabilities found at C-1/C-2. Furthermore, only military high performance engines can be tested here, thus limiting testing versatility.

Functional radiography is possible for J-2; however, only the TELS X-ray source is recommended for this application.

8.1.4 Test Cell J-5

It is recommended that the L-6000 mounted external to the chamber firing through aluminum "windows" be used in conjunction with LMSCs conceptually designed imaging system. The detector must be internally mounted, as in all the other cases, but can be adequately positioned for the coverage needed.

8.1.5 Equipment Commonality/Portability

8.1.5.1 TELS Source

The key to equipment commonality for AEDCs altitude testing is the acceptance of the TELS X-ray source design for use in C-1/C-2 and/or J-2. Development of this unit is recognized as being several years away; however, the functional advantages of using this compact, relatively lightweight unit for the altitude application compensate for the time delay. All major X-ray programs at AEDC for turbine engines would, in effect, use a single type X-ray unit. The interchangeability of spare parts, portability of equipment, standardization of operations, and repair would accrue as major advantages to both facilities. Some consideration could be given to the purchase and use of only one unit for all test sites; however, this decision would require detailed study. The design of a single positioning capsule for this source acceptable to TELS and the altitude chambers could be accomplished, thereby allowing full cross-use of one machine. Scheduling may be the major obstacle.

8.1.5.2 LINATRON 3000

If the turbine altitude X-ray project requires faster implementation than is possible under the development schedule for the TELS unit, an acceptable substitute for C-1/C-2 would be the LINATRON 3000. (It cannot be used at J-2 except with the "bubble" concept). This approach would, however, provide AEDC with three separate X-ray sources on-site: the L-6000 at J-5, TELS at the loads simulator facility, and L-3000 at C-1/C-2.

There is also some question regarding the L-3000 positioning capability for large-diameter transport (e.g. JT9D) engines in C-1/C-2. Determination of its adequacy would require a closer investigation should this unit be considered for C-1/C-2.

8.1.6 Mobile Operations Center

One component that might be common to all altitude cells at AEDC would be a mobile operations center. Figure 47 illustrates the possible layout of such a structure. This mobile center could house the following:

- X-ray source power center and modulator
- X-ray and detector controls
- Positioner controls
- Interlock and controls for the radiation safety system
- Dark room facility

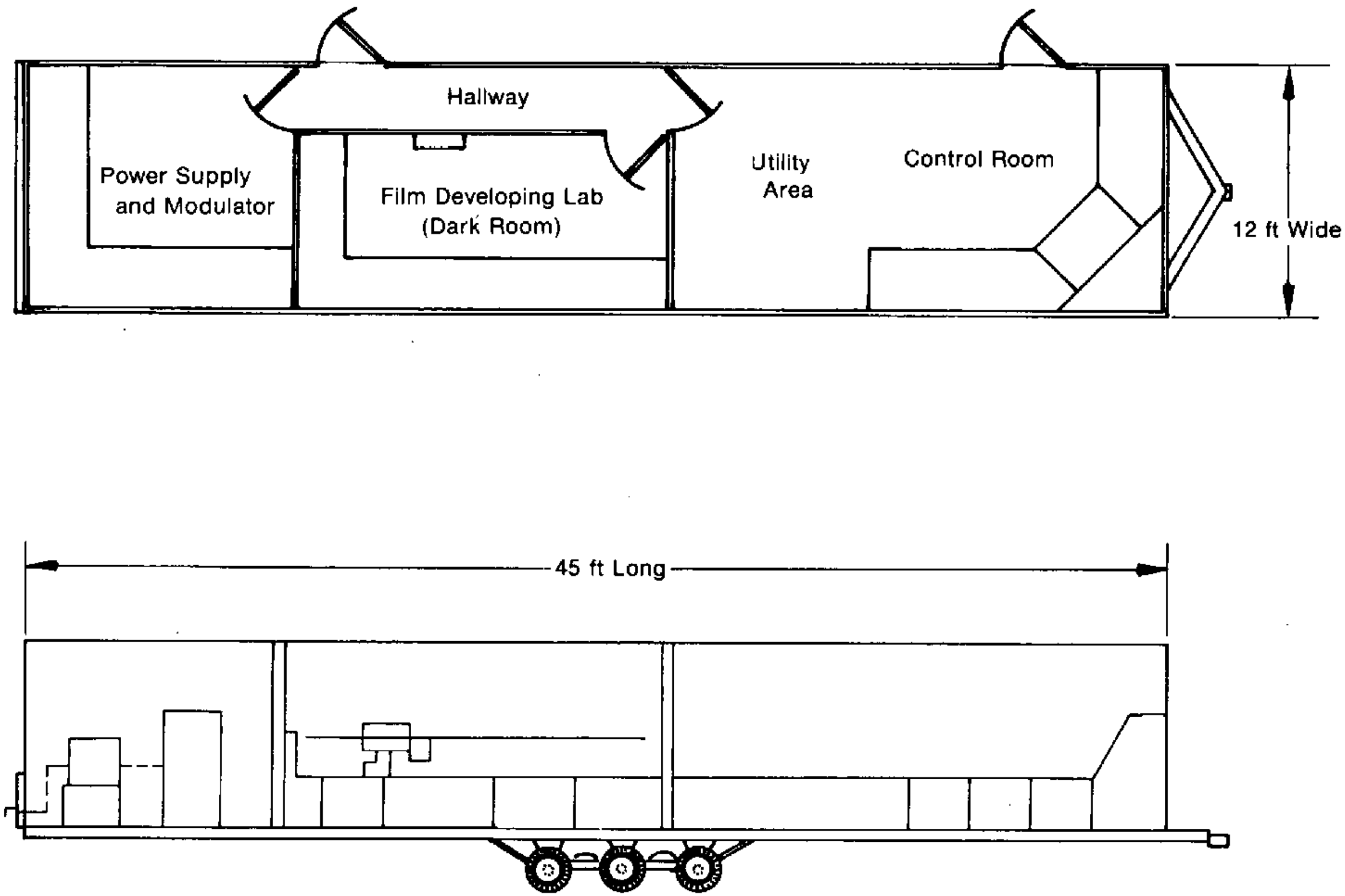

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Figure 47. Mobile Control/Process Trailer

Two-way audio and visual communication would be required between the engine control room and the X-ray system control room. In addition, a direct readout of specific engine data such as revolutions per minute and thrust with capability of direct interface of these parameters to the X-radiographic system controls would be required.

Each test cell utilizing the X-radiographic system would have permanently installed power cabling, coolant, and control lines to the site of the mobile structure from the X-ray source. These services would terminate in junction boxes at the site with appropriate connectors for trailer hook-up.

The application of a mobile operations center would, of course, preclude simultaneous X-radiography at more than one site. It appears that the most advantageous use of this type of control facility would be between C-1/C-2 and J-2 where the TELS source and detector would be common to both locations. At J-5, the L-6000 and control systems would be more functional if they were permanently installed. This would make the turbine engine and rocket engine programs independent radiographic systems and would afford increased versatility for both areas.

Table 14 presents a summary of the recommended X-ray systems for each test location.

TABLE 14. RECOMMENDATION SUMMARY

	Test Cells			
	J-1	*C-1/C-2*	*J-2*	*J-5*
Turbine Engine Cells	No System	TELS Source and LMSC Detector Mounted Internally	TELS Source and LMSC Detector Mounted Internally	—
		Mobile Control Center for J-2, C-1/C-2		
Solid Propellant Rocket Motor Cell	—	—	—	L-6000 mounted externally with LMSC detector inside. Controls and power systems installed permanently on-site.

REFERENCES

1. "Turbine Engine Loads Simulator Radiographic System Detailed Definition Study," AEDC Contract F40600-77-C-002, January 1978.

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3. Tennessee State Regulations for Protection Against Radiation, Division of Industrial and Radiological Health, Tennessee Dept. of Public Health, Nashville, TN, 1972.

4. Medical X-ray and Gamma-ray Protection for Energies up to 10 MeV Structural Shielding Design and Evaluation, National Council on Radiation Protection and Measurements, NCRP Report No. 34, Washington, DC, 1970.

5. Nondestructive Inspection Methods, Air Force Technical Manual, T.O. 33B-1-1, TM43-0103, 1 February 1966, Change 13-1, January 1976.

6. Industrial Hygiene Standard No. 53, 27 June 1975, ARO, Inc.

7. Swanson, W. P., "Radiation Parameters of Electron Linear Accelerators," Stanford Linear Accelerator Center Report No. 2092, March 1978.

8. Radiological Safety in the Design and Operation of Particle Accelerators, National Bureau Standards Handbook 107, ANSI Standard N43.1-1969, June 1970.

9. Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities, National Council on Radiation Protection Report No. 51, 1977.

10. Trubey, D. K., "Single Scattering Approximation to the Solution of the Gamma-Ray Air Scattering Problem," Nuclear Science and Engineering, Vol. 10, p 102-116, 1961.

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12. Lockheed Missiles & Space Company, Inc., High Energy Radiography, by E. A. Yates, et al, Technical Report Number 4, LMSC-D407227, November 1974.

13. Carslaw, H. S., and J. C. Jaeger, *Conduction of Heat in Solids*, Oxford Clarendon Press, p 56, 1947.

14. Jaeger, R. C., Engineering Compendium on Radiation Shielding, Vol. 1, ed. et. al., 1968.

APPENDIX A

EQUIPMENT SPECIFICATIONS

TELS X-RAY — LINATRON® 2000 AND 6000

1.0 GENERAL DESCRIPTION

The specifications for the proposed TELS X-ray source are summarized in table A-1. This system satisfies the performance requirements established by the Pratt & Whitney Aircraft study. The size and weight are compatible with the mounting and positioning structure.

TABLE A-1. DESIGN SPECIFICATIONS FOR X-RAY SOURCE

Electron Beam Energy	8 MeV
Central Axis X-ray Intensity	3,000 rads/min at 1m minimum
Focal Spot Size	1.25 mm dia maximum
Pulse Length	5 μsec
Pulse Rate	50 to 200 lb/sec
X-ray Field Angle	1 to 8 deg (conical)
Beam Stability	Output within 80% of maximum within 0.05 sec after "beam-on"
X-ray Head	
Volume	13 ft^3 maximum
Weight	1,000 lb maximum
Maximum Acceleration	15g (21g objective)
Ambient Temperature	5 to 40°C
Modulator	
Volume	75 ft^3
Weight	1,500 lb
Control Console	
Volume	2.5 ft^3
Weight	60 lb
Utilities	
Power	208/120v Y-connected, 60a, 60 Hz 5-wire. Regulated ±5%. Maximum steady-state demand 20 kva.
Coolant Water	5 gal/min at maximum temperature of 27°C.

The source system consists of three separate physical modules. The X-ray head contains the electron accelerator and those components that must be located close to it, the microwave and high-voltage components. This module is the source of the X-ray beam, and must be small and light enough to be positioned easily about the object to be radiographed. It is in the X-ray head that the conflict between the requirements for high radiation rate and small size and weight must be resolved. This is the area of major innovation in the present proposal.

The modulator unit contains the high-voltage power supply and pulse modulator, as well as the trigger generator and synchronization circuits, voltage regulator, low-voltage power supplies, and most of the protective, interlock and control circuits. The coolant circulating system and heat exchanger, while separately housed, is mounted adjacent to the modulator. In the TELS installation, the source of high-voltage insulating gas (Freon 12 or sulfur hexafluoride) will also be located and regulated at the modulator enclosue. The components of this module are basically the standard ones employed in radiographic LINATRONS. Some modifications, both electrical and physical, are necessary to meet the special requirements of the TELS installation.

The third module is the control console. This unit contains the circuits, switches and indicators necessary to monitor and control the operation of the accelerator from a remote location. Again, it is proposed to employ a standard LINATRON control cabinet, physically adapted for mounting in the central TELS control console. The circuits and panel controls must also be modified to provide the pulse synchronization and other special interface functions required in the TELS system.

EQUIPMENT SPECIFICATIONS

LINATRON® 2000

RADIOGRAPHIC LINEAR ACCELERATOR

FD 144826

Figure A-1. X-ray Head Cabinet

SCOPE

This specification provides requirements for a high energy x-ray linear accelerator system for use in radiography inspection of thick sections of various materials. The system shall be capable of continuous operation at 8 MeV and 2000 rad/min at 1 meter, and shall consist of the following assemblies:

The x-ray head containing the necessary circuitry, accelerator beam centerline assembly, microwave generator, pulse transformer and cooling system. The accelerator beam centerline assembly is to be a sealed standing wave type "S" band unit with no demountable vacuum joints and an integral electron gun and x-ray target.

The control console containing controls, meters, switches, and interlocks as required for remote control of the x-ray system.

The modulator cabinet containing a line-type modulator, power supplies and closed circuit cooling water system including heat exchanger and temperature controller.

The motorized positioning system for the x-ray head. (Optional)

The interconnecting cable between the control console, the modulator, and the x-ray head.

ACCELERATOR REQUIREMENTS

PERFORMANCE SPECIFICATIONS

Electron Beam Energy: The nominal energy of the electron beam shall be 8 MeV.

X-ray Beam Intensity and Field Flatness: The rated intensity of the x-ray beam at full power and nominal energy shall be as follows:

Central axis:	2000 R/min (minimum) at 1 meter
Edge of 15° cone:	60% of central axis intensity (minimum uncompensated)

Total collimator cone angle is 30°.

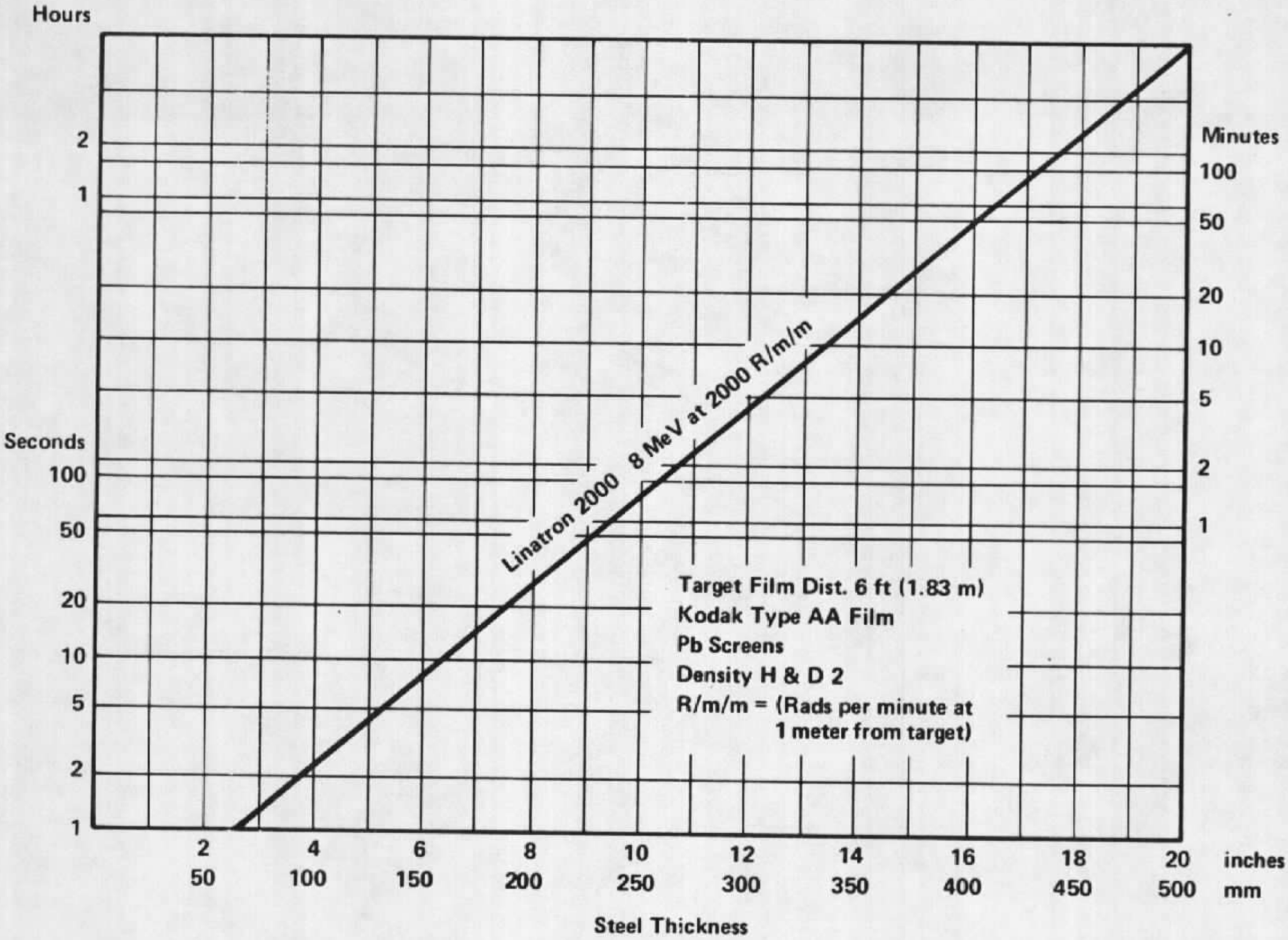
Typical exposure curve for steel is shown on following page.

X-ray Beam Stability: The time required for the x-ray beam to stabilize after initiation of the "beam on" signal shall not exceed five seconds.

Focal Spot Size: The focal spot size shall not exceed 2mm in diameter.

Radiographic Quality: The system shall be capable of demonstrating a radiographic quality level of 1–2 T or better (as defined in ASTM-E142) in steel over a range of 3" (76 mm) to 15" (380 mm).

Field Size: 39" (1 m) diameter field at 6' (1.83 m) target film distance.



TYPICAL EXPOSURE CURVE FOR STEEL

EQUIPMENT FEATURES

General Arrangement: The x-ray head shall be capable of being mounted on trunnions in a yoke which may in turn be mounted on an overhead crane or other handling or positioning equipment. The x-ray head shall also be capable of being lifted and positioned using built in skids on its base.

Weights and Dimensions: Maximum component weights and dimensions are to be as follows:

Component:	X-Ray Head	Modulator Cabinet	Control Console
Height:	29" (73.7 cm)	87.5" (222 cm)	10" (25 cm)
Width:	28" (71.2 cm)	48" (122 cm)	20" (51 cm)
Depth:	66" (168.1 cm)	30" (76.3 cm)	15" (38 cm)
Weight:	2,000 lbs (900 kg)	1,500 lbs (680 kg)	60 lbs (27 kg)

X-Ray Beam Direction: The central axis of the x-ray beam shall be at a perpendicular to the x-ray head mounting trunnions. The unit shall be operable at any angle about the vertical axis and from +45° to -95° about the horizontal axis. Rotation and elevation of the head may be accomplished by an optional motor driven yoke with control switches located on a pendant or other suitable positioning system. The unit shall be capable of full rated output in any position selected.

X-Ray Collimator: A conical shaped x-ray beam collimator shall be incorporated to provide total cone angle of 30°.

Leakage Radiation: Average leakage radiation measured over any 100 cm^2 area at 1 meter from the target outside the primary radiation collimator shall not exceed 0.1% of the central axis intensity.

Beam Direction Finder: The x-ray generating unit shall be fitted with a laser beam direction finder which projects a light beam along the x-ray centerline. The spot of light projected shall be clearly visible on the workpiece under any reasonable room lighting conditions and usable target film distances.

Cabinet Enclosures: All components at the x-ray head and modulator cabinet shall be fully contained within grounded metal enclosures. Doors shall be fitted with detachable hinges so that they can be removed for service accessibility.

CONTROLS

General: The control console shall be equipped with the controls and monitors necessary for routine operation and self-protection of the machine. It shall also include circuits to interrupt the operation of the machine when triggered by inputs from external interlock devices supplied by others. The control console shall be designed to be conveniently placed on and operated from one-half of a standard office desk top.

Operating Modes: Five separate operating modes shall be provided as follows:

Power OFF:	Power OFF to entire system
Standby:	X-ray beam OFF; rf generator filament at reduced voltage; gun filament at reduced voltage
Ready:	X-ray beam OFF; dosimeter reset for next exposure
Beam ON:	X-ray beam ON
Complete:	Exposure complete, X-ray beam OFF

Pulse repetition frequency shall be continuously variable from a control on the console over a minimum range of 3 to 1.

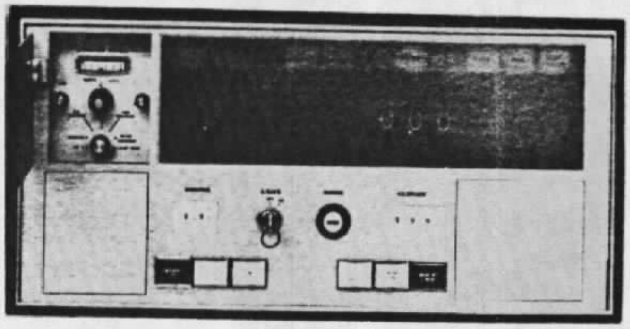
Safety: Voltage in the control console shall be limited to 28 volts except for very low current applications such as the operation of visual counter tubes.

Time Clocks: Time monitors shall be provided in the modulator to keep a continuous record of the filament and beam time.

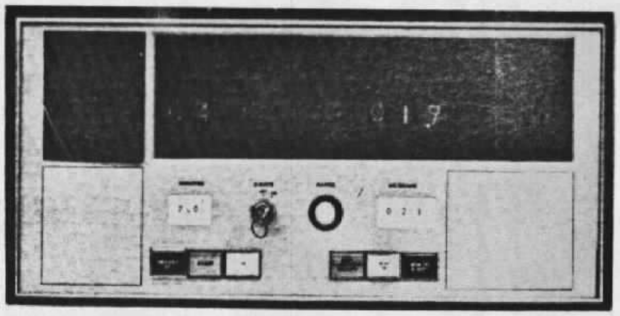
X-Ray Beam Exposure Control and Display: A system shall be provided that will allow the operator to preset a value of total x-ray exposure up to 99,900 rad in steps of 100 rad, or up to 9,990 rad in steps of 10 rad. When the preset exposure is reached the x-ray beam shall shut off automatically. A radiation exposure sensing instrument shall be an integral part of the system. A digital readout shall display the accumulated exposure and a meter shall provide a readout of instantaneous x-ray beam intensity in rad/min at 1 meter from the target, at the control console.

Interlocks and Protective Systems: Internal equipment subsystem and personnel safety interlocks shall be provided. Each interlocked function shall have a pilot light that indicates the status of that function. A terminal board shall be provided for connecting external safety interlocks supplied by others to the machine controls.

Intercom System: A two-way intercom system shall be provided between the x-ray head and/or modulator cabinet and the control console.



LINATRON CONTROL CONSOLE
(Lamp Test with Monitor Panel Open)



LINATRON CONTROL CONSOLE
(Beam ON)

UTILITIES

Power: The system shall be capable of operation from 208 Y/120V, 80A 60Hz, or 380 Y/220V, 50A 50 Hz, circuit plus ground (5-wire system) regulated to $< \pm 5\%$. Maximum steady state demand shall be less than 15 KVA.

Secondary Cooling Water: The accelerator shall be capable of operation with cooling water supplied from a normal city water system (50 ppm or less dissolved solids content is desirable).

Water quantity required shall not exceed 4 gal (15ℓ) /min during normal operation, and 2 gal (7.5ℓ) /min in standby condition at a maximum temperature of 80° F (27° C). Maximum shut off pressure is 150 psi (10 at.); minimum pressure difference between supply and return line is 30 psi (2 at.). Water may be recirculated or may be piped to a drain as desired.

Ventilation: The modulator stand shall be capable of operation in a room ventilated to remove a minimum of 5 kW of heat.

ACCELERATOR MOUNTING SYSTEMS (OPTIONAL)

GENERAL

A variety of mounting systems shall be available. The system selected will depend upon the flexibility of use required. Following are examples of such systems.

OVERHEAD BRIDGE CRANE

An electric overhead crane shall be supplied for support and maneuvering of the x-ray head. Positioning of the accelerator shall be through a motorized telescoping apparatus suspended from a motorized trolley. All crane equipment shall be in accordance with CMAA No. 70 specifications for Electric Overhead Traveling Cranes.

Span: The bridge shall have a rail to rail span of ____ feet (____ m). Crane rails and supports shall be furnished by the customer.

Lift: The x-ray beam shall be capable of being positioned over the range from _____ feet (______) above the floor, to _____ feet (_____ m) above the floor. The lift specified shall be compatible with the rail and overhead obstruction heights available.

Yoke: A motorized yoke for rotating and elevating the x-ray head shall be mounted on the telescoping hoist; the yoke shall be capable of minimum horizontal rotation of $\pm 175^\circ$ from a selected axis and vertical rotation of +45° or -95° from horizontal.

Speeds: Bridge and trolley speed shall be continuously variable up to 20 ft (6.1m)/min; hoise speed shall be 10 ft (3.5m)/min single speed. Yoke horizontal rotation and head vertical rotation speed shall be about .75 rpm single speed.

Control: All movements of the x-ray generating unit and the operation of the beam axis defining light shall be controlled from a single pendant pushbutton station suspended by chain or cable from the trolley. The pushbutton station shall be capable of being key locked to prevent unauthorized operation.

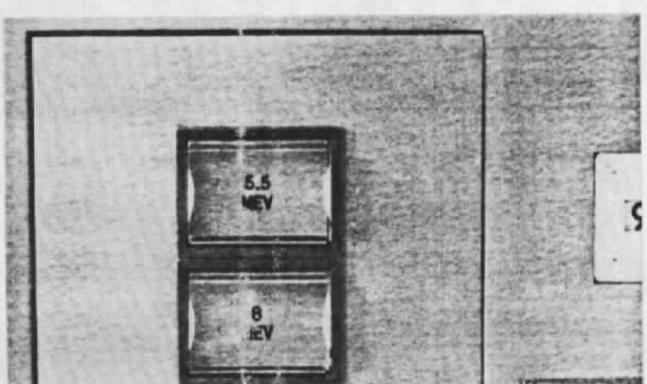
MOTORIZED YOKE

A motorized yoke similar to that described in "Yoke" and "Speeds" above, but modified for suspension from a motorized fork truck overhead monorail, or other overhead suspension system may be provided.

OPTIONS

The following options are available.

1. Shock mount, transportation skids, and quick disconnect cables for transportable applications.
2. Energy switching to allow operator selection of either of three nominal electron energies—5.5, 8 or 10 MeV — from a switch on the control console. When supplied with this option, the rated output of 2000 rads per minute at one meter is achieved at 8 MeV and output is reduced as energy is increased or decreased. The switch panel for this option is located on the lower left side of the console as shown below.



INSTALLATION AND ACCEPTANCE

Prior to shipment, Varian will perform certain acceptance tests, including spot size measurement, vertical and horizontal symmetry plots, X-ray energy determination, and X-ray output. These tests are described in Paragraphs 1, 2 and 3 below. The customer will be invited to witness these tests if he desires and a report of the results will be submitted to the customer upon successful completion of these tests.

After installation, final customer acceptance shall be based upon the successful completion of the remaining tests described in Paragraphs 4, 5, 6 and 7 below.

1. Demonstrate spot size to be 2.0mm or less in diameter. The demonstration will be made by the use of a spot size camera which consists of an optically aligned welded assembly of photoetched plates or an equivalent system. The plates are 10" (254mm) long and contain 6 mil longitudinal holes on 10 mil centers. Dental film, Polaroid 3000 film, or other equivalent film exposed through the spot size camera will yield a series of dots corresponding to the holes in the plates superimposed on the image of the x-ray spot. The spot size is determined directly by counting the dots covered by the spot. 4 dots = 1 millimeter.
2. Demonstrate central axis x-ray beam intensity by means of measurements using an appropriate secondary standard such as a Victoreen condenser R meter or Baldwin Farmer dosimeter. Vertical and horizontal x-ray beam symmetry shall be demonstrated from intensity plots over the collimated field. The appropriate buildup cap for machine energy shall be used in making all measurements.
3. Demonstrate x-ray beam energy. A measurement of narrow beam HVL in steel shall be used as the method of determining x-ray energy. Measurements shall be performed using an appropriate secondary standard as in Paragraph 2 above. The third or successive HVL shall be used in determining the energy using Table 16, Section 27 of the *Non-Destructive Testing Handbook*, Vol. 1, Ronald Press (1954), New York. Steel plates used for this measurement will have a larger area than the x-ray field and the secondary standard shall be located at least 1 meter from the plates at their thickest dimension during the test.
4. Demonstrate operation of each interlock, undercurrent and overload device designed to protect the machine and personnel.
5. Demonstrate operation of auxiliary equipment, such as yoke manipulator, telescoping hoist and trolley and/or bridge crane, if provided.
6. Film sensitivity shall be demonstrated using the method outlined in ASTM E-142 68. The test material shall be larger than the film holder. Appropriate side and back shielding shall be allowed, if necessary, to reduce scattered radiation. Penetrameter sensitivity of 1% shall be demonstrated through 3" (76mm), 6" (152mm), 9" (228mm) and 15" (380mm) of steel.
7. The Linac shall perform continuously for an 8-hr period at rated energy and output with no equipment failures and no more than 8 momentary interruptions in an 8-hr period. (A momentary interruption is defined as loss of electron beam for no more than 5 minutes.

EQUIPMENT SPECIFICATIONS

LINATRON® 6000

RADIOGRAPHIC LINEAR ACCELERATOR

Linatron X-ray Head

SCOPE

This specification provides requirements for a high energy x-ray linear accelerator system for use in radiographic inspection of thick sections of various materials. The system shall be capable of continuous operation at a fixed beam energy of 15 MeV, at an x-ray output greater than 6000 rad/min, at 1 meter unflattened and shall consist of the following major components:

The x-ray generating unit or x-ray head contains the accelerator beam centerline assembly, microwave generator, pulse transformer, and necessary interconnecting circuitry and cooling lines. The accelerator beam centerline assembly is to be a standing wave type "S-band" unit. The microwave generator is to be a single 5 Mw klystron.

The control station consists of a desk, a control console containing controls, meters, switches, and interlocks, as required for remote control of the x-ray system and a drawer containing the printed circuit card rack, power supply, and system monitor panel.

The modulator cabinet contains a line-type modulator, power supplies, and power distribution.

The pump stand contains the pump, reservoir, and controls for the internal closed circuit cooling water system.

The interconnecting cables between the control console, the modulator, pump stand, and the x-ray head.

ACCELERATOR REQUIREMENTS

PERFORMANCE SPECIFICATIONS

Electron Beam Energy: The nominal energy of the electron beam shall be 15 MeV.

X-Ray Beam Intensity: The rated output of the x-ray beam at full power and nominal energy shall be 6000 rads/min at one meter on the central axis. A typical exposure curve is shown on the following page.

Field Size: The field shall be defined by a collimator having a right pyramid shape and total angles of 15° vertical and 20° horizontal.

Flatness: At 6° either side of the central axis, the minimum intensity shall be 40% of the central axis intensity with no beam flattening filter.

Flattening Filter: A field flattening filter which may be rapidly inserted and removed shall be included to provide a minimum intensity of 3000 rads/min. at 1 meter with a flatness of ±10% of average intensity over a total cone of 15°.

Symmetry: At 6° either side of the central axis, the beam asymmetry shall be $< \pm 5\%$.

X-Ray Beam Stability: The time required for the x-ray beam to stabilize after initiation of the "beam on" signal shall not exceed five seconds.

Focal Spot Size: The focal spot size shall not exceed 3mm in diameter.

Radiographic Quality: The system shall be capable of demonstrating a radiographic quality level of 1–2T or better as defined in ASTM E 142 in steel over a range of 3" (76mm), to 18" (460mm) of steel.

EQUIPMENT FEATURES

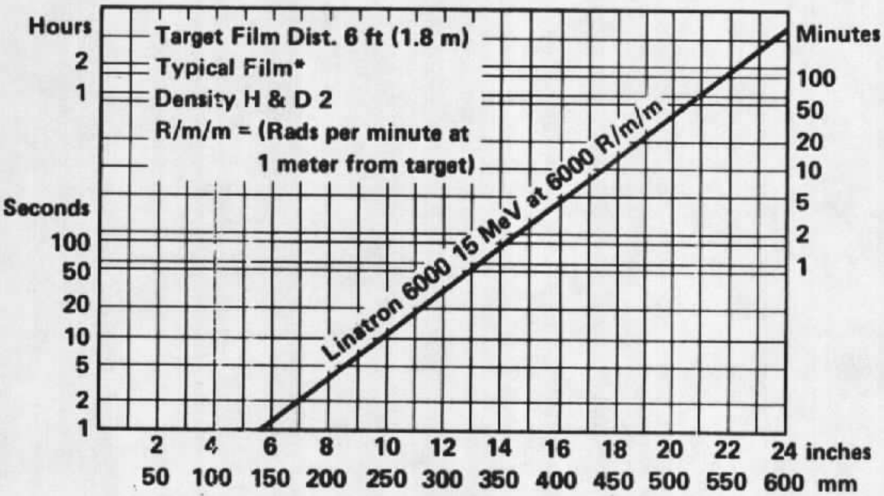
General Arrangement: The x-ray head shall be capable of being mounted on trunnions in a yoke which may in turn be mounted on an overhead crane or other handling equipment or positioning equipment.

Weights and Dimension: Component weights and dimensions are as follows:

Component	Height	Width	Depth	Weight
Console*	10" (25 cm)	25" (64 cm)	18" (45 cm)	50 lbs (23 kg)
Modulator	84" (220 cm)	50" (127 cm)	48" (120 cm)	2,300 lbs (1,050 kg)
Pump Stand	67" (170 cm)	48" (120 cm)	48" (120 cm)	1,500 lbs (680 kg)
Head	60"** (152 cm)	52" (132 cm)	99" (252 cm)	8,600 lbs (3,900 kg)
Power Center	33" (84 cm)	51" (120 cm)	36" (91 cm)	900 lbs (408 kg)
Chiller (Optional)	68" (190 cm)	54" (137 cm)	49" (125 cm)	2,400 lbs (1,090 kg)

*Card rack and DC Power Supply are included in desk supplied with the control console.

**Height does not include lifting eyes.



Steel Thickness

TYPICAL EXPOSURE CURVE FOR STEEL

X-Ray Beam Direction: The central axis of the x-ray beam shall be at a perpendicular to the mounting trunnions. The unit shall be rotatable about the vertical axis and from +45° above to −95° below the horizontal axis. Rotation and elevation of the unit shall be accomplished by optional motor driven yoke with control switches located on a pendant. The unit shall be capable of full power output in any position selected.

Leakage Radiation: Average leakage radiation measured over any $100cm^2$ area at 1 meter from the target outside the cone defined by the primary x-ray collimator shall not exceed 0.1% of the central axis intensity. The high energy photons of the Linatron 6000 generate neutron radiation leakage which must also be considered in facility shielding design. Special shielding has been incorporated into the Linatron 6000 to limit neutron leakage to approximately 0.1% REM/x-ray rad in the forward direction outside the collimator and 0.01% REM per x-ray rad in all other directions.

Beam Direction Finder: The x-ray generating unit shall be fitted with a laser beam direction indicator which projects a light beam along the x-ray beam centerline. The spot of light projected shall be clearly visible under any reasonable room lighting conditions and usable target film distances. The laser shall conform to BRH class II requirements.

Cabinet Enclosures: All components at the x-ray head and modulator cabinet shall be fully contained within grounded dust-tight sheet metal enclosures. Doors shall be detachable so that they can be removed for service accessibility.

CONTROLS

General: The control console shall be equipped with the controls and monitors necessary for routine operation and self-protection of the machine. It shall also include circuits to interrupt the operation of the machine when triggered by inputs from external interlock devices supplied by others. The control console shall be furnished with a standard office desk which also includes a drawer which contains a printed circuit board card rack assembly and DC power supply.

Operational Modes: Five separate operational modes shall be provided as follows:

Beam ON: X-ray beam ON

Complete: Exposure complete; x-ray beam OFF

Ready: X-ray beam OFF; dosimeter reset for next exposure

Standby: X-ray beam OFF; water pump on, water heater on, vacuum pumps on

Power OFF: Power OFF to entire system

X-Ray Beam Exposure Control and Display: A radiation exposure sensing ion chamber shall be an integral part of the system. A digital readout shall display the accumulated exposure at the control console. A second meter shall be provided at the control console to give a readout of instantaneous x-ray beam intensity in rad/min at 1 meter from the target. The system shall allow the operator to preset the required x-ray exposure. When the preset exposure is reached, the x-ray beam shall automatically shut off.

Interlocks and Protective Systems: Internal equipment subsystems and personnel safety interlocks shall be provided. Each interlocked function shall have a panel light that indicates the status of that function. A terminal board in the modulator shall be provided for connecting external safety interlocks supplied by others to the machine controls.

***Kodak Type AA, Dupont Type NDT 70 or equivalent.**

UTILITIES

Power: The system shall be capable of operation from a single 45 KVA power source of 208 or 240 volts, 60 Hz, 3-phase, 3-wire, plus ground (4-wire system) 125 amp minimum per leg regulated to ±5%. For 50 Hz operation provide 380/220 volts 50 Hz 3-phase, 3-wire, plus ground (4-wire system) 75 amp minimum per leg regulated to ±5%.

Secondary Cooling Water: The system shall be capable of operation using cooling water supplied from a normal city water system (50 ppm or less dissolved solids content is desirable). Water quantity required shall not exceed approximately 12 gallons (45ℓ) per minute during normal operation and 8 gallons (20ℓ) per minute in standby at a maximum temperature of 80°F (27°C). Maximum shut-off pressure is 150 psig (10 atm); minimum pressure difference between supply and return line is 35 psi (2.4 atm). Water may be recirculated or may be piped to a drain as desired.

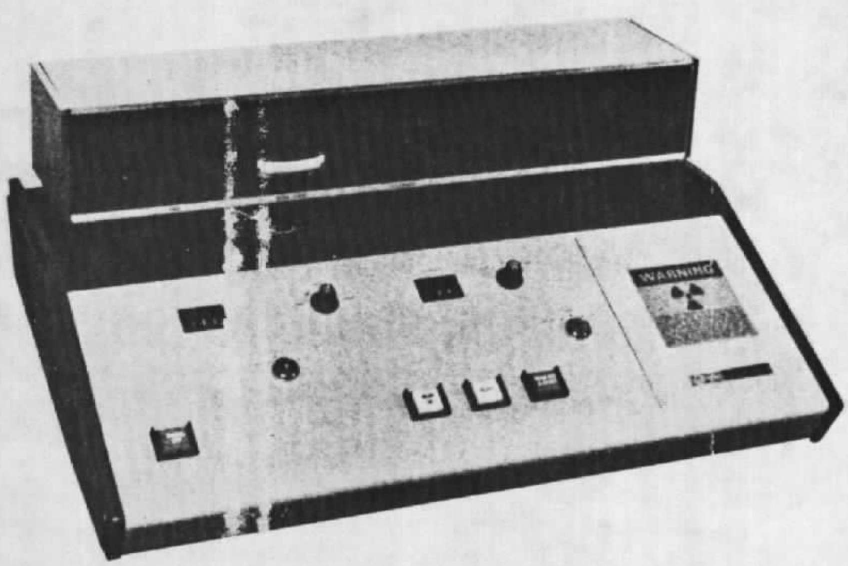
ENVIRONMENT AND VENTILATION

Indoor Service: Temperature in the room housing the x-ray generator shall be in the range of 40°F (5°C) to 105°F (40°C) with a relative humidity not exceeding 95%. This room shall be ventilated to remove approximately 5 kw of heat. The room housing the modulator shall be ventilated to remove approximately 5 kw of heat.

Prior to order, provide Varian Associates with the following environmental and use information for the Linatron system:

- Indoor or outdoor installation.
- Anticipated use factors.
- Ambient temperature range.
- Percent relative humidity range.
- Primary cooling water temperature range.
- Other unusual factors such as dust, exposure to direct sunlight, etc.

The information will be reviewed by Varian Associates and, depending on the circumstances, minor modifications to the system may be recommended. For example, a heater may be added to the closed circuit water cooling system to handle low ambient temperature conditions, or a cooling system may be recommended in the case of unusually high ambient temperatures.



Linatron 6000 Control Console

OPTIONS

The following options are available:

1. Small focal spot (1.5mm).
2. Special collimator configuration.
3. Chiller for external closed circuit water cooling.*

*If the option is ordered an additional 15 KVA separate electrical service is required.

ACCELERATOR MOUNTING SYSTEMS (OPTIONAL)

GENERAL

A variety of mounting systems shall be available. The system selected will depend upon the flexibility of use required. Following are examples of such systems.

OVERHEAD BRIDGE CRANE

An electric overhead bridge crane shall be supplied for support and maneuvering of the x-ray head. Positioning of the accelerator shall be through a motorized telescoping apparatus suspended from a motorized trolley. All crane equipment shall be in accordance with Varian specifications.

Span: The bridge shall have a rail-to-rail span of ____feet (_____m). Crane rails and supports shall be furnished by the customer.

Lift: The x-ray beam shall be capable of being positioned over the range from ____feet (_____m) above the floor to ____feet (_____m) above the floor. The lift specified shall be compatible with the rail and overhead obstruction heights available.

Yoke: A motorized yoke for rotating and elevating the x-ray head shall be mounted on the telescoping hoist; the yoke shall be capable of minimum horizontal rotation of ±175° from a selected axis and vertical rotation of +45° above or −95° below horizontal.

Speeds: Bridge and trolley speed shall be continuously variable up to 20 feet (6.1 m)/minute hoist speed shall be 10 feet (3.5 m)/minute single speed. Yoke horizontal rotation and head vertical rotation speed shall be about 0.5 rpm single speed.

Control: All movements of the x-ray generating unit and the operation of the beam axis defining light shall be controlled from a single dust-tight, pendant pushbutton station suspended by chain or cable from the trolley.

MOTORIZED YOKE

A motorized yoke similar to that described in "Yoke" and "Speeds" above, but modified for suspension from a motorized overhead suspension system, may be provided.

Linatron Modulator Cabinet

INSTALLATION AND ACCEPTANCE

Prior to shipment, Varian will perform certain acceptance tests at the factory, including spot size measurement, vertical and horizontal symmetry, beam flatness, x-ray energy determination, and x-ray beam intensity. These tests are described in the following Paragraphs 1, 2, 3, 4 and 5. If the customer requests at the time of order, he will be invited to witness these tests at the factory in Palo Alto, California. A report of the test results will be submitted to the customer.

Following installation, final acceptance shall be based upon the successful completion of the remaining tests described in Paragraphs 6, 7, and 8 at the installation site. Materials for site tests must be supplied by the customer.

1. **Spot Size:** The spot size is measured with the use of a spot size camera which consists of an optically aligned welded assembly of photo-etched plates or an equivalent system. The plates are 10" (254mm) long and contain longitudinal holes 6 mils long on 10 mil centers. Dental film, Polaroid 3000 film, or other equivalent film exposed through the spot size camera will yield a series of dots corresponding to the holes in the plates superimposed on the image of the x-ray spot. The spot size is determined directly by counting the dots covered by the spot. 4 dots = 1 millimeter.

2. **Central Axis X-Ray Beam Intensity:** The x-ray beam intensity is measured at the point of maximum intensity buildup. The buildup is produced with an appropriate thickness lucite cap placed in front of the dosimeter.* Measurements are made at one meter from the x-ray target. The measurements are performed with a secondary standard such as a Victoreen R-meter or a Farmer dosimeter.

3. **Vertical and Horizontal Beam Symmetry:** The symmetry is measured at the conjugate points corresponding to the 6° points of the X-ray cone. Asymmetry is the ratio, in percent, of the difference of the intensity of the conjugate points to the central axis intensity. The asymmetry of these points will be within ±5%. The measurement is performed at the point of maximum X-ray buildup with the use of lucite as a buildup medium, as described in item 2, above. The detector is located at least one meter from the target. The ionization chamber is typically scanned across the output beam horizontally and vertically through the central axis point, and a plot of the output for both axes as a function of position is produced.

4. **Flatness:** At the points described in item 3 above, the intensities shall be greater than or equal to 40% of the central axis intensity, with no compensation filters. The measurement is performed with the same setup as item 3.

5. **X-Ray Beam Energy:** Measurement of the percentage depth-dose curve in water shall be used to determine beam quality. The appropriate ionization chamber, such as one of those described in item 2 above, shall be used as the detector for these measurements.

The depth-dose curves in water shall include the depth of maximum buildup and further depth, at 50% of maximum intensity.

6. **Interlocks:** Operation of each interlock, undercurrent and overload device designed to protect the machine and personnel shall be demonstrated.

7. **Auxiliary Equipment:** Operation of auxiliary equipment, such as yoke manipulator, telescoping hoist and trolley and/or bridge crane, if provided shall be demonstrated.

8. **Radiographic Quality:** Penetration sensitivity shall be demonstrated using the method outlined in ASTM E 142. The test material shall be larger than the film holder. Appropriate side and back shielding shall be allowed, if necessary, to reduce scattered radiation. A penetrameter sensitivity of 1–2T shall be demonstrated through 3" (76mm), 6" (152 mm), 10" (254mm), and 18" (457 mm) of steel.

9. **Extended Operation:** Continuous performance for an 8-hour period at rated energy and output with no equipment failures and no more than 8 momentary interruptions in an 8-hour period shall be demonstrated. (A momentary interruption is defined as loss of beam for no more than 5 minutes.)

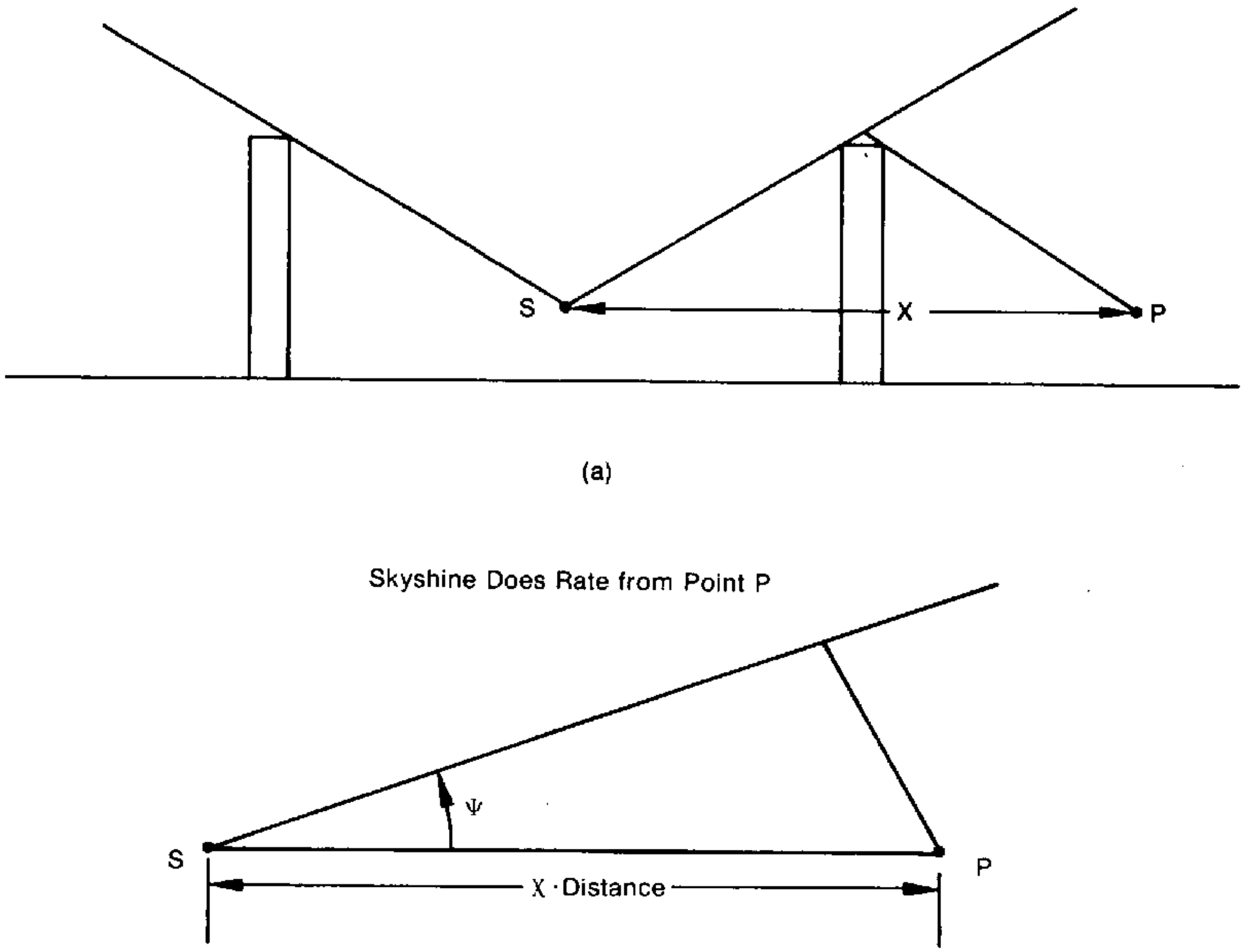
*Maximum buildup occurs with approximately 3 cm of lucite.

NOTE: All specifications subject to change without notice.

APPENDIX B

SKYSHINE CALCULATIONS[10]

Consider a monoenergetic isotropic source of photons $Q/4\pi$ (photons/sec-srd^{-1}) for the geometry shown in figure B-1a and as shown simplified in figure B-1b.



FD 144838

Figure B-1. Skyshine Dose from Source of Protons to Point P

The dose at point P from this source at S is given by:

$$D_{total}(E\ \Psi) = \int_{\Omega} \frac{Q}{4\pi} D(E,\ X,\ \Psi)\ d\Omega$$

where Ω is the solid angle defined, for example, by a region excluded by the shielding wall and where $D(E, X, \Psi)$ are given in figures 10-15 of Trubey (0.6 to 12 MeV) in units of [$r\text{-}hr^{-1}\text{-}\gamma^{-1}\text{-}sec$] as a function of distance in air.

Consider an infinitely thin, but impervious semicircular shield of height (radius) h, shown in figure B-2 which approximates (conservatively) a rectangular wall h + 2h.

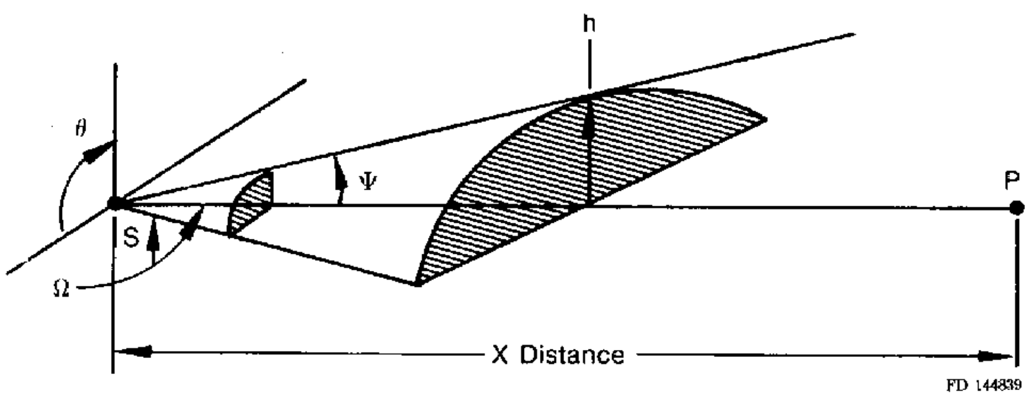


Figure B-2. Skyshine from a Semicircular Infinitely Thin Impervious Shield

The dose rate at P is obtained by integrating over the solid angle defined by

$$\Delta\Omega: \begin{cases} \Psi_o \le \Psi \le \pi \\ O \le \theta \le \pi \text{ (upper plane only)} \end{cases}$$

Hence

$$D(E,\ \Psi,\ X) = \frac{Q}{4\pi} \int_{O}^{\pi} \int_{\Psi_o}^{\pi} D(\Psi,\ E,\ X) \sin \Psi\ d\ \Psi\ d\ \theta$$

or

$$D_{total}(E,\ \Psi,\ X) = \frac{Q}{4} \int_{\Psi_o}^{\pi} D(E,\ \Psi,\ X) \sin \Psi\ d\ \Psi$$

See figure B-3 for a plot of $D(E, \Psi, X)$ for D(2 MeV, 20 ft Ψ) from figure 12 of Trubey.

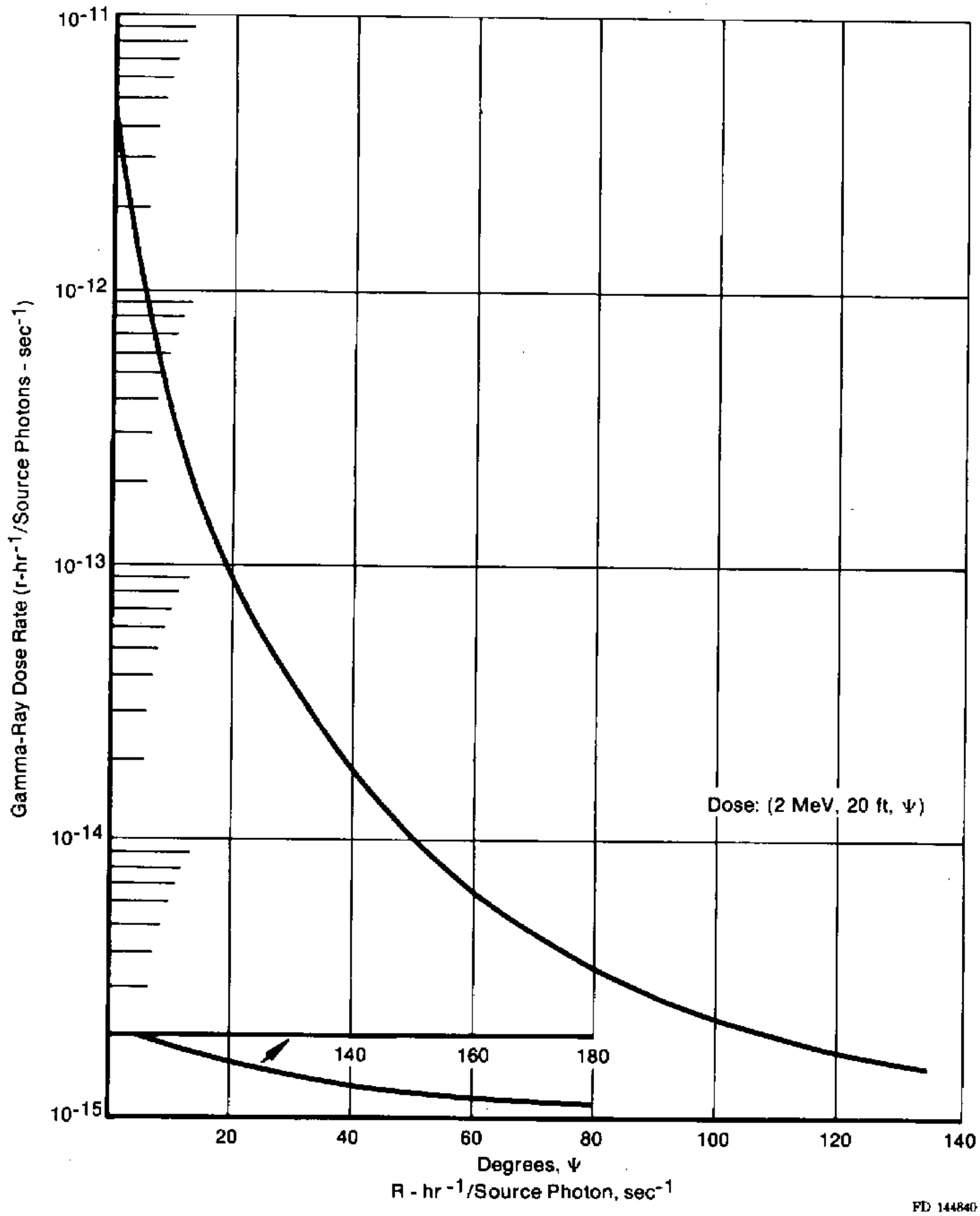


Figure B-3. Skyshine Dose Rate Function

For a LINATRON® 2000 assume:

- E = 2 MeV
- X = 20 ft

Table B-1 is a tabulation for the integration plot of skyshine from this X-ray accelerator shown in figure B-4. A similar plot is included for the LINATRON® 6000.

Column 2 is taken from figure B-3.
Column 4, Y = Dose(2 MeV, 20 ft Ψ) sin Ψ

$$Q = \text{source } (\gamma/\text{sec-srd}^{-1}) = 1.2 \times 10^{5} \times 0.001 \frac{\text{R}}{\text{h}} \times \frac{1\ \gamma \cdot \text{cm}^{-2}}{8.33 \times 10^{-10}\text{R}} \times \frac{1}{3600 \text{ sec}} \times 4\pi \times 10^{4} \text{ cm}^{2}$$

$$= 5.04 \times 10^{12}\ \gamma/\text{sec}$$

and Column 7:

$$D_t \frac{\text{mR}}{\text{hr}} = \frac{Q}{4} \Sigma\, Y\, \Delta\, \Psi \times \frac{\pi}{180} \times 1000 = 2.2 \times 10^{13}\ \Sigma\, Y\, \Delta\, \Psi$$

(See figure B-4 for plot of Column ⑦).

TABLE B-1. DOSE RATE MATRIX

① Ψ	② Dose(2 MeV, 20 ft, Ψ)	③ sin Ψ	④ Y = ② × ③	⑤ Y Ψ	⑥ E Y Ψ	⑦ D_{total} (mR/hr)
175	1.1×10^{-15}	0.087	0.10×10^{-15}	3.1	4.1	9.0
165	1.2	0.259	0.31	5.4	9.5	2.1×10^{-1}
155	1.3	0.423	0.54	7.7	1.72×10^{-14}	3.8
145	1.4	0.574	0.77	1.1×10^{-14}	2.82	6.2
135	1.5	0.707	1.1	1.5	4.32	9.5
125	1.8	0.819	1.5	1.8	6.12	1.4×10^{0}
115	2.0	0.906	1.8	2.2	8.32	1.8
105	2.3	0.966	2.2	2.8	1.11×10^{-13}	2.5
95	2.8	0.966	2.8	3.2	1.43	3.2
85	3.2	0.996	3.2	3.9	1.82	4.0
75	4.0	0.966	3.9	4.9	2.31	5.1
65	5.4	0.906	4.9	5.6	2.87	6.3
55	7.0	0.819	5.6	9.4	3.81	8.4
45	1.3×10^{-14}	0.707	9.4	1.4×10^{-13}	5.24	11.5
35	2.5	0.575	1.4×10^{-14}	2.6	7.85	17.3
25	5.6	0.423	2.6	4.1	1.20×10^{-12}	26.4
15	1.6×10^{-13}	0.259	4.1	7.1	1.91	42.1
5	8.1×10^{-13}	0.087	7.1			

NOTE: For these calculations dose decreases linearly with distance. As an example, the dose at 100 ft will be 0.2 the dose given in figure B-4 for 20 ft.

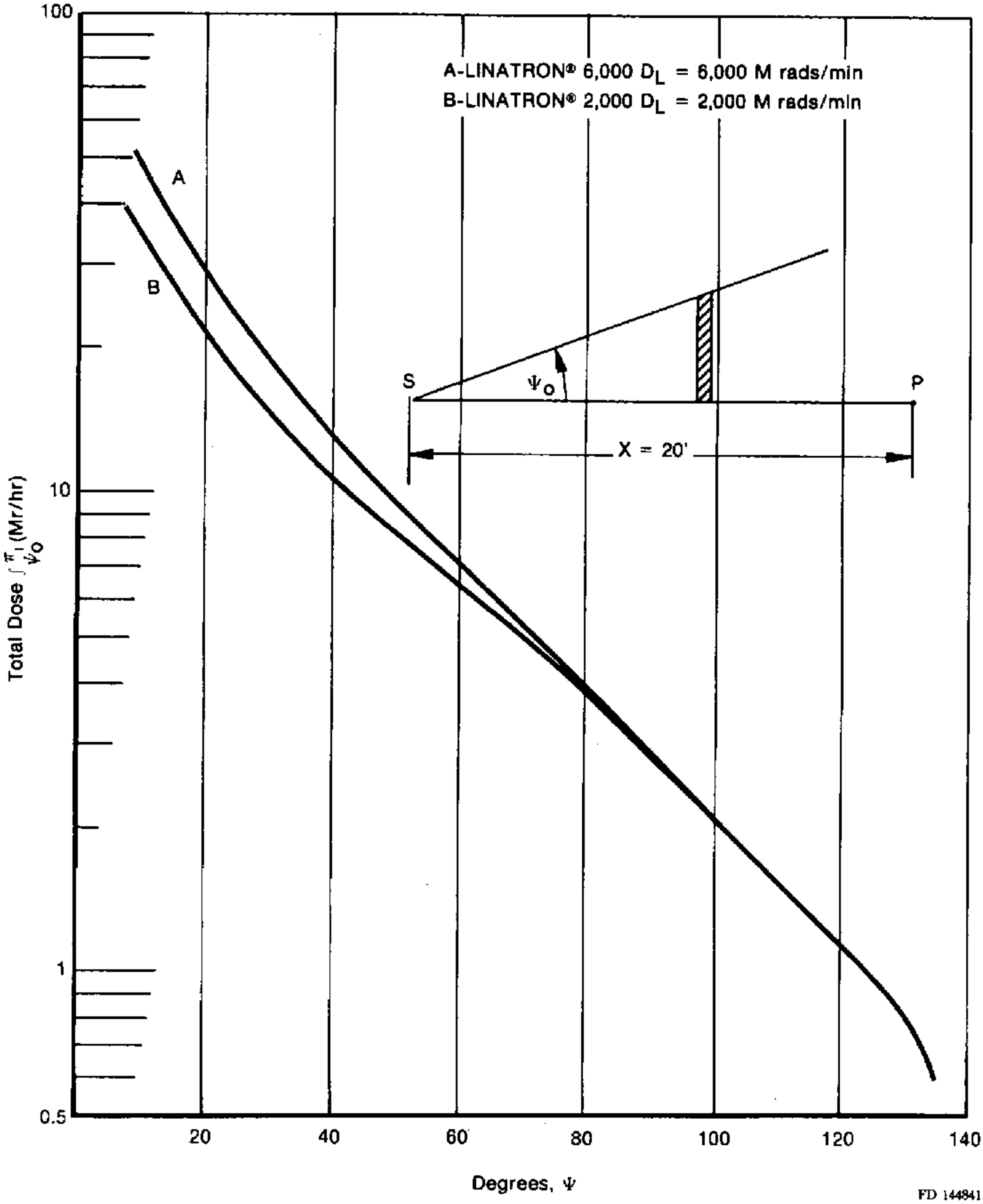
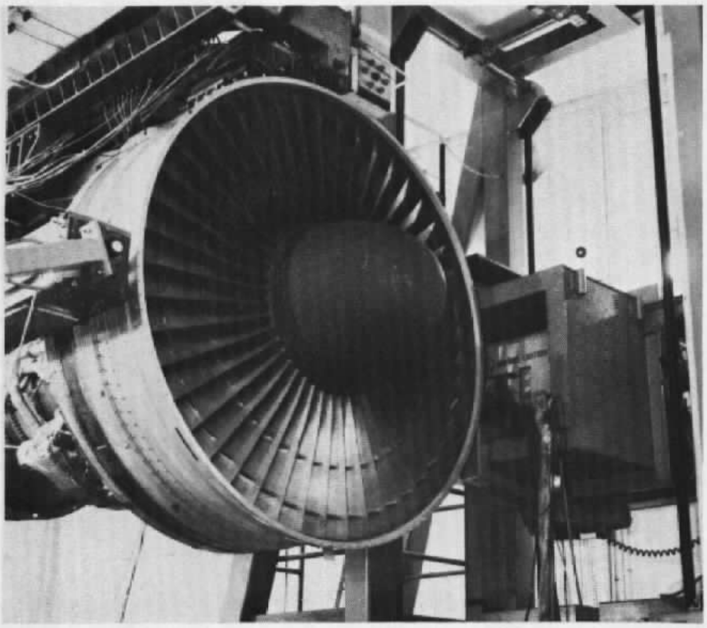


Figure B-4. Skyshine Dose Rate vs Angle Defined by Source and Shield

APPENDIX C
EQUIPMENT AND FACILITIES

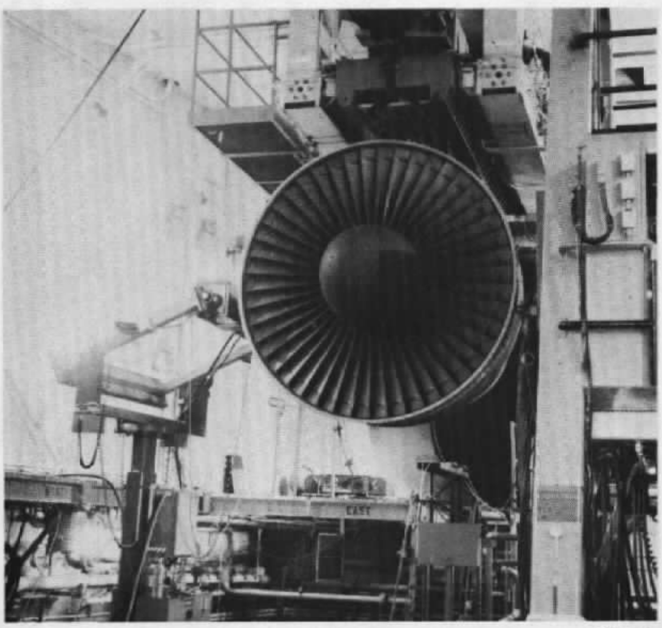
The following photographs include equipment and facilities considered in this study program:

- Figures C-1, C-2, and C-3 show the JT9D (P-8) X-ray facilities.
- Figures C-4 and C-5 show the J-1 test cell.
- Figures C-6, C-7, and C-8 show the J-2 test cell and control rooms for the J-1/J-2.
- Figure C-9 shows the J-5 test cell at AEDC.
- Figures C-10, C-11, C-12, C-13, and C-14 show various X-ray sources considered in the program.
- Figures C15 and C16 are the detector and control console, respectively for the Lockheed High-Energy Real-Time Radiography System.



CN 54916

Figure C-1. JT9D Mounted in P&WA's P-8 X-ray Facility at Middletown, Conn. X-ray Head Is Shown on the Right (Mounted Inside Lead Vault)

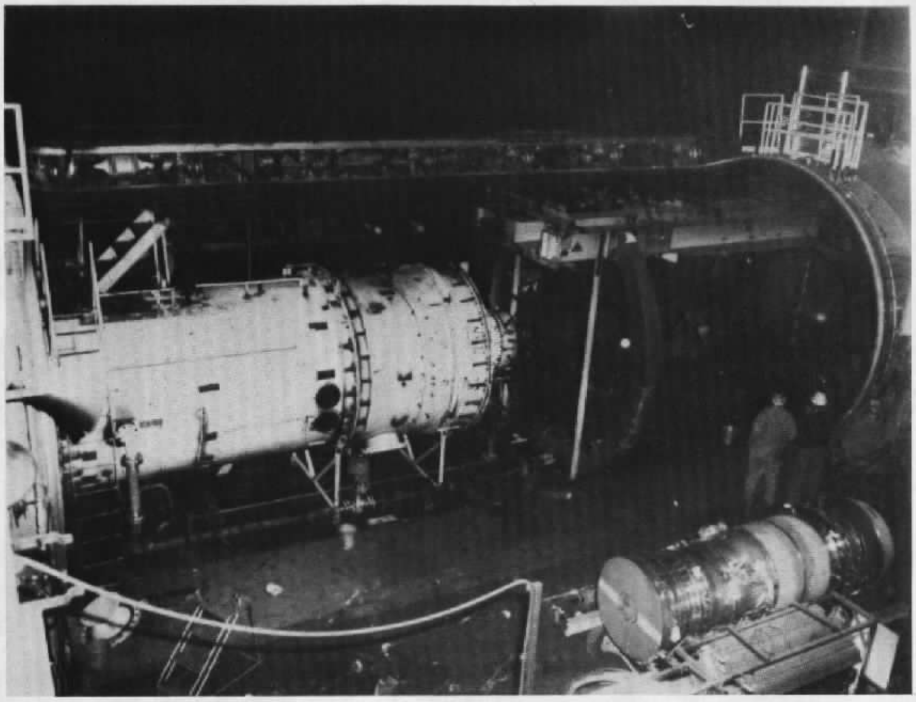


CN 54914

Figure C-2. JT9D Mounted in P&WA's P-8 X-ray Facility at Middletown, Conn. Video System Is on the Left

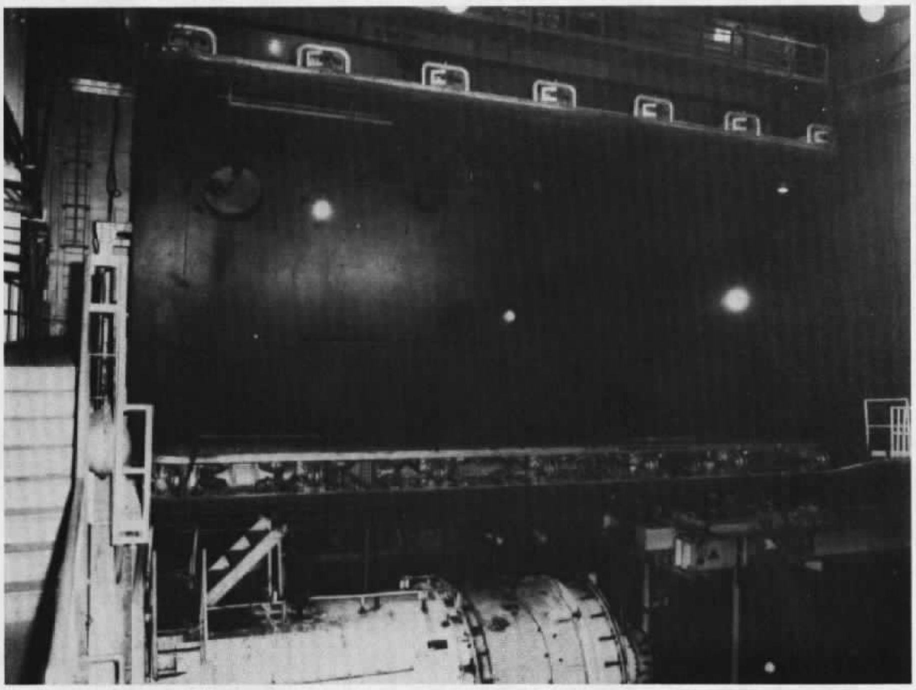
76-441-0061-C

Figure C-3. P-8 X-ray Facility Control Console



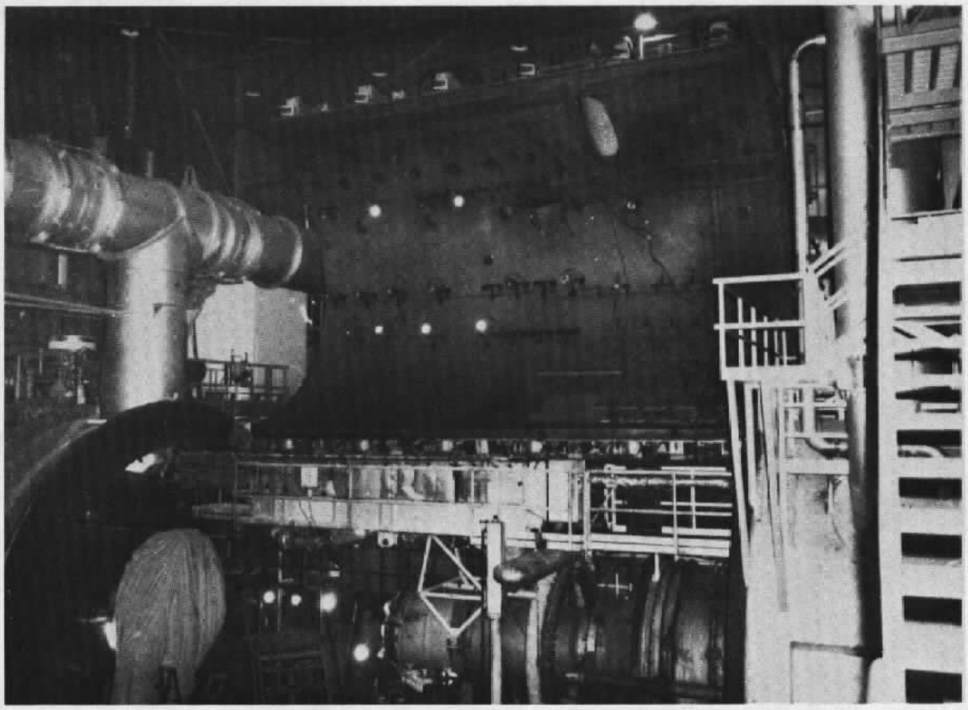
FC 60235

Figure C-4. J-1 Test Cell (AEDC) Showing Engine Support Mount



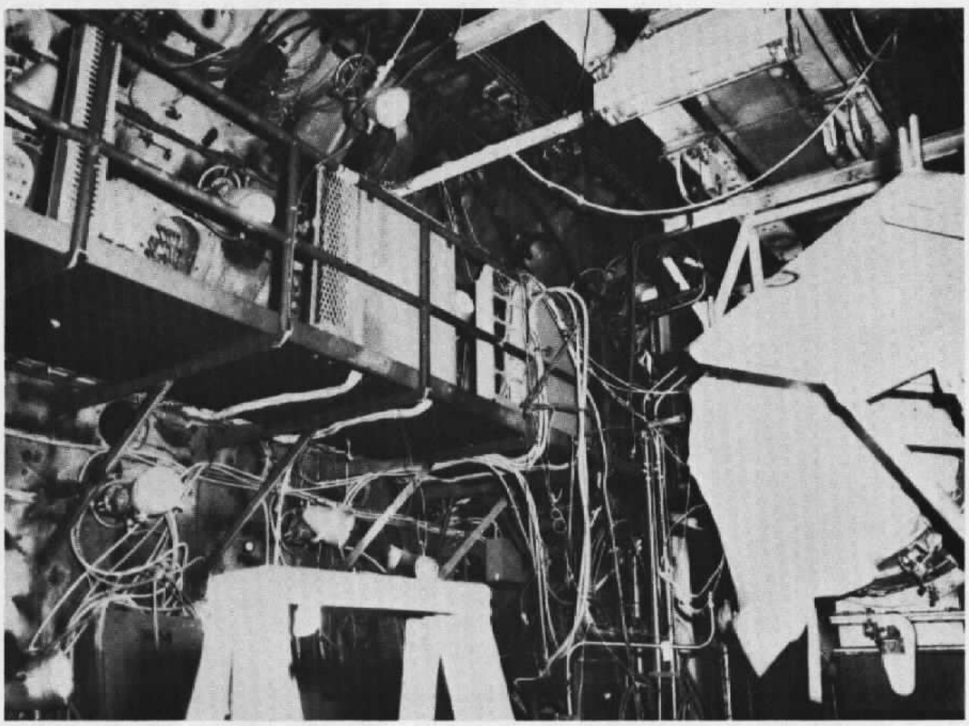
FC 60234

Figure C-5. J-1 Test Cell (AEDC) Showing Open Hatch



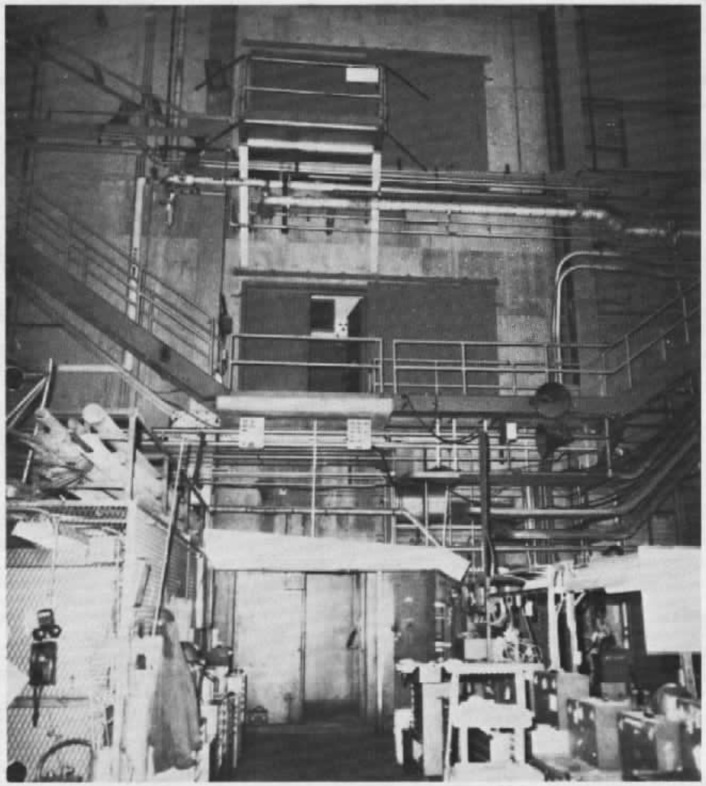
FC 60122

Figure C-6. J-2 Test Cell (AEDC) Showing Hatch Open and Engine Support Mount, Air Flow Is from Right to Left



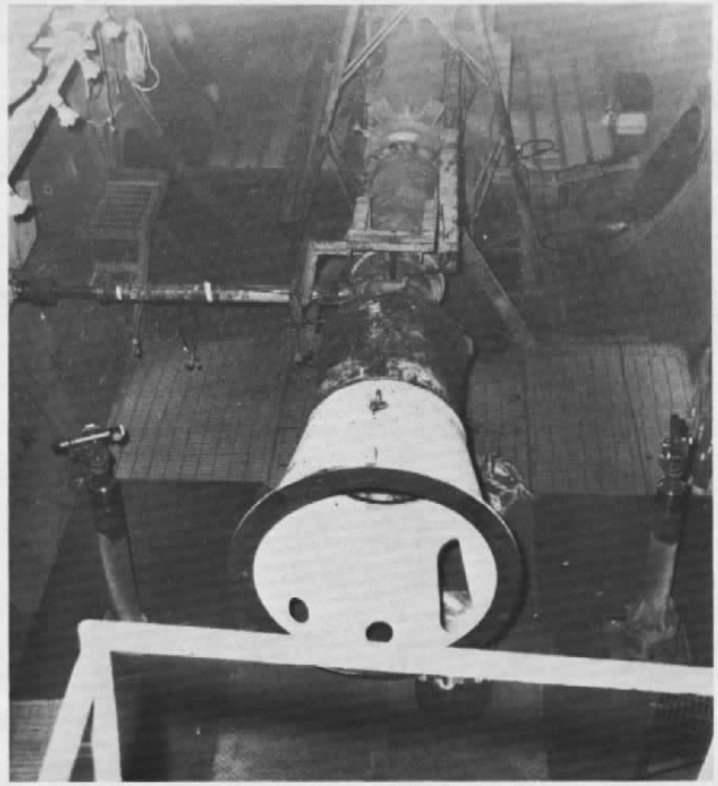
FC 60125

Figure C-7. J-2 Test Cell (AEDC) Showing Existing Platform, Cabling, etc. Which Requires Relocating for X-ray Detector Positioning



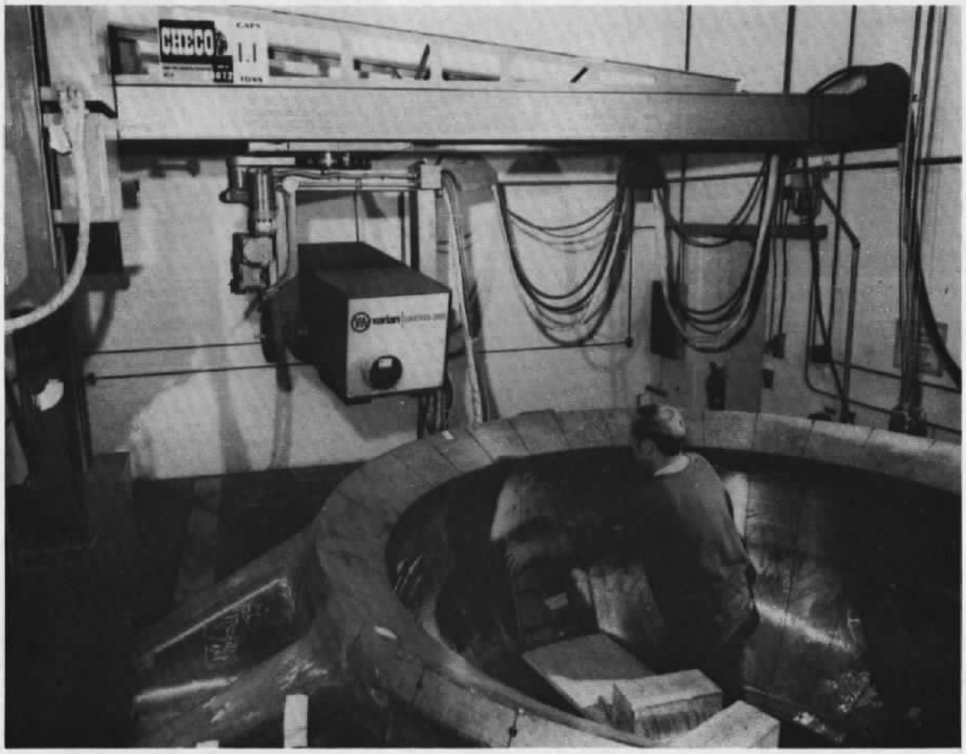
FC 60126

Figure C-8. J-1 and J-2 Control Rooms



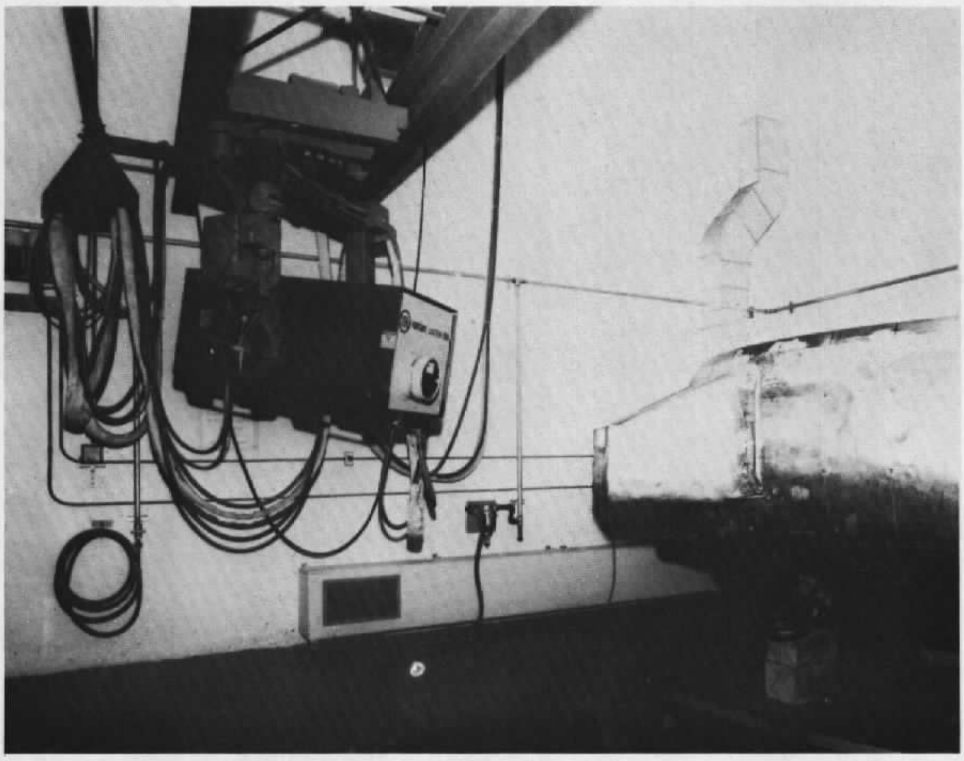
FC 60123

Figure C-9. J-5 Test Cell (AEDC) Interior Looking in Direction of Thrust



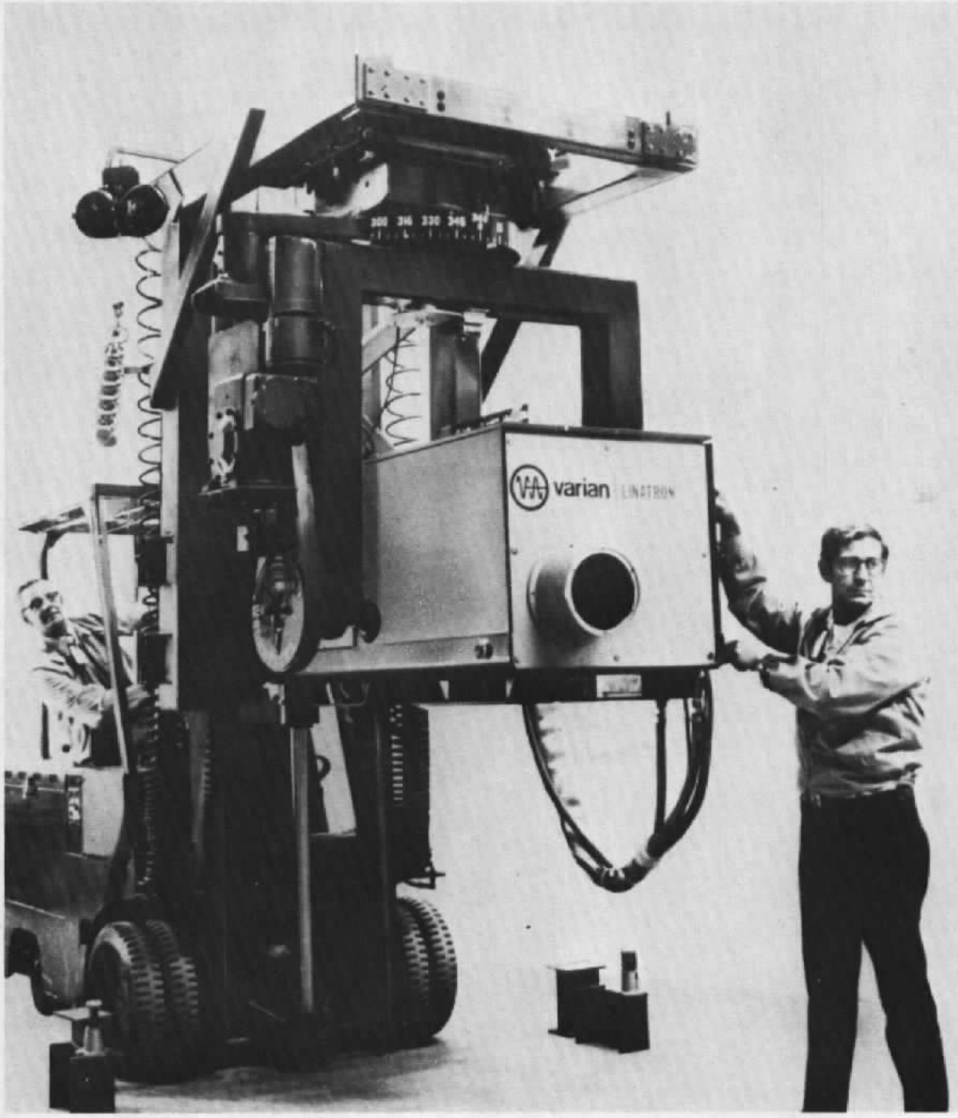
FC 60239H

Figure C-10. Varian's LINATRON 2000 Mounted on Traveling Jib Crane



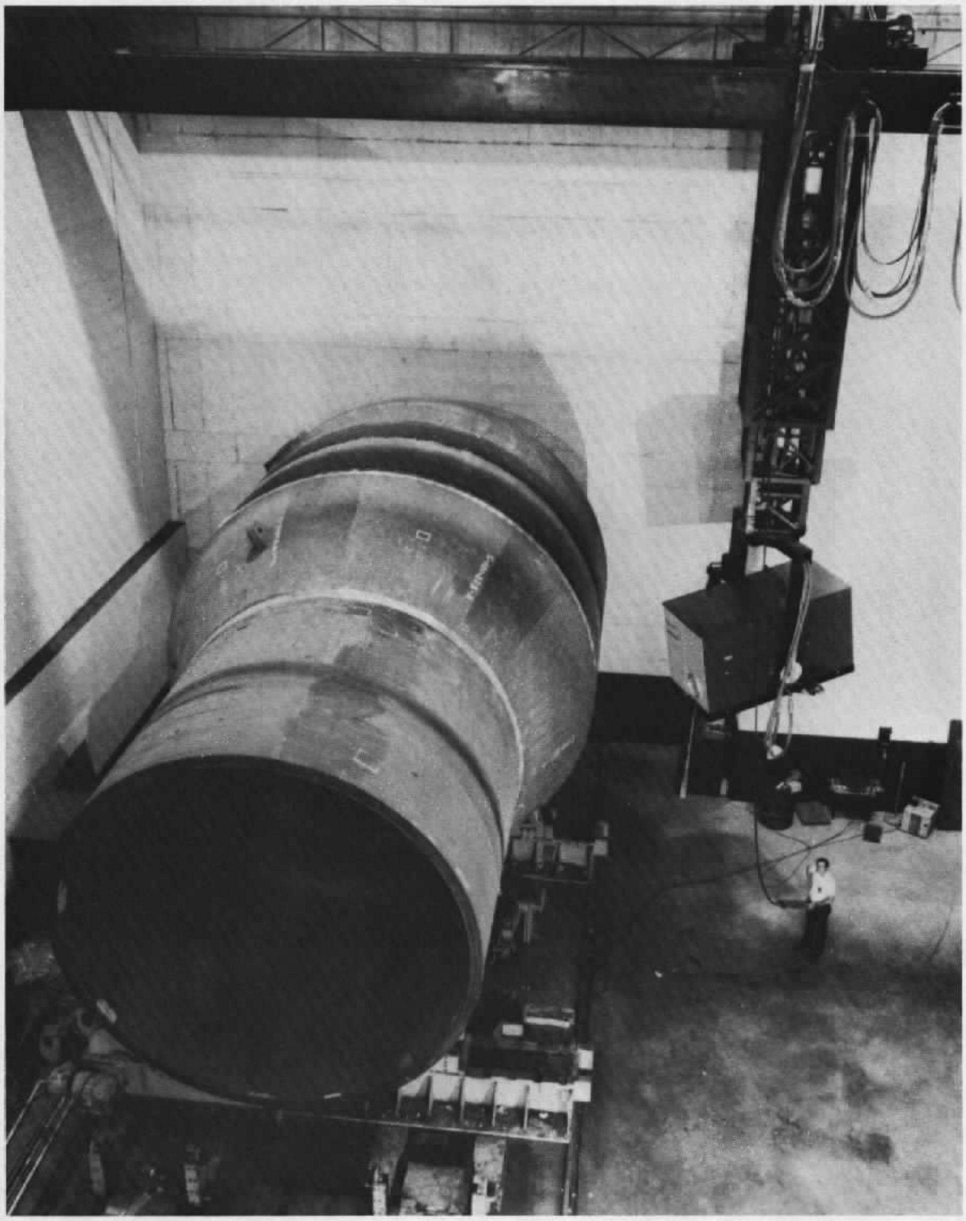
FC 60240H

Figure C-11. Varian's LINATRON 2000 on Jib Crane Showing TILT and Rotating Mechanisms



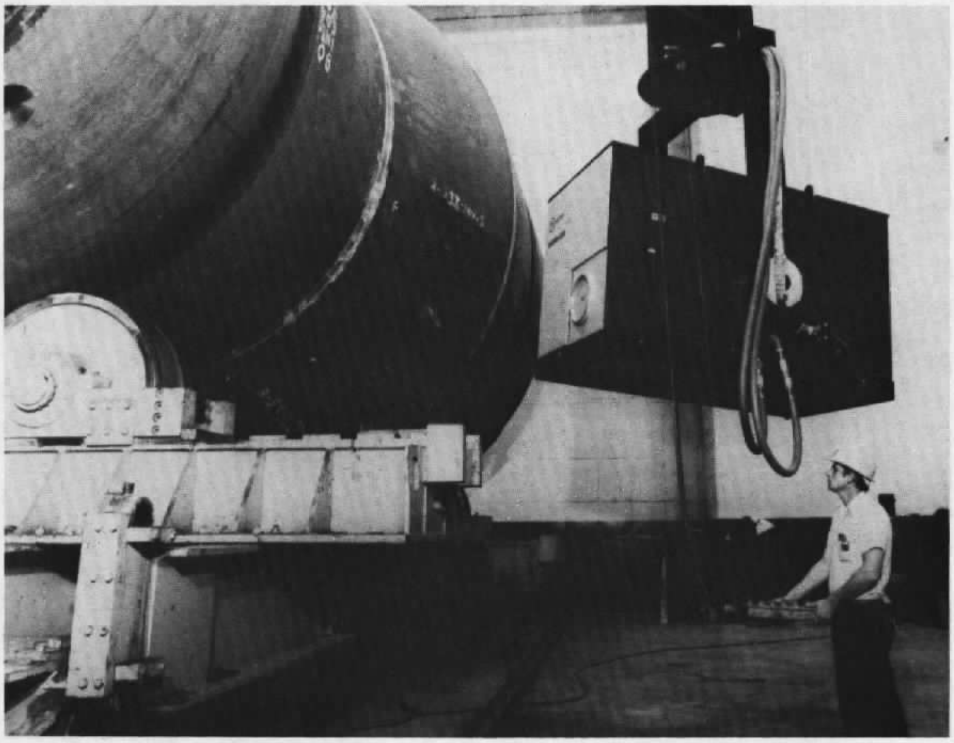
FC 60241H

Figure C-12. Portable X-ray Source Positioning Mechanism



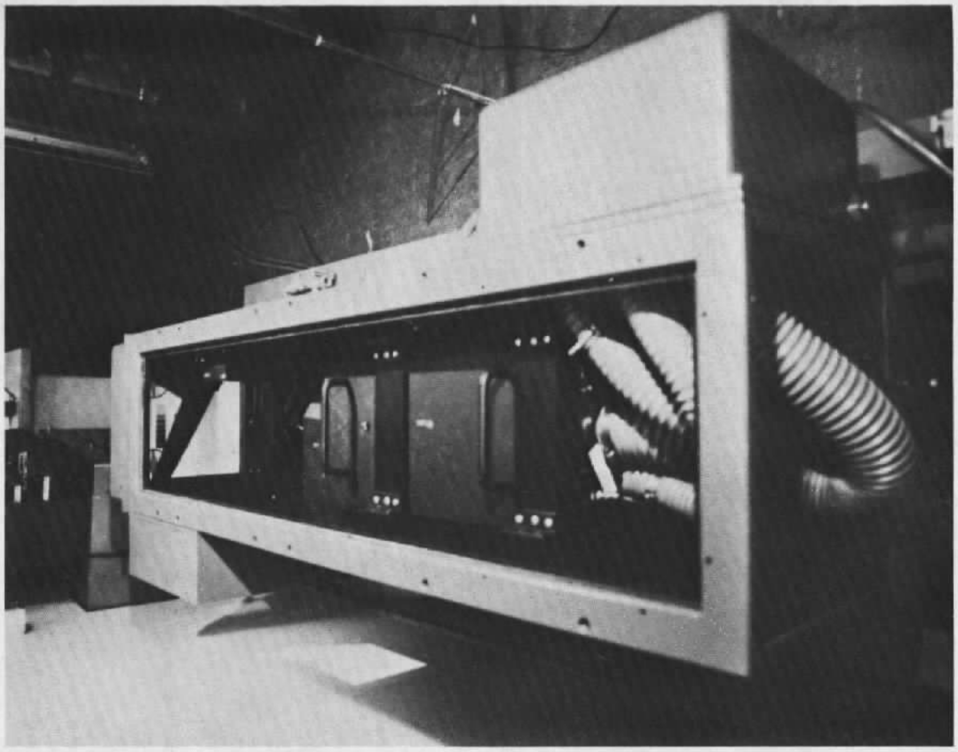
FC 60238H

Figure C-13. Varian's LINATRON 6000 Mounted on Bridge Crane With Telescoping Mount (Similar to that Proposed for J-5)



FC 60237H

Figure C-14. LINATRON 6000 Operator Positioning Machine With Crane Pendant Control



FC 61228

Figure C-15. Detector for the Lockheed High-Energy, Real-Time Radiography System (HERTRS)

FC 61229

Figure C-16. Console for the Lockheed High-Energy, Real-Time, Radiography System for Inspection of Solid Propellant Motors for the Trident Submarine-Launched Missile Program

APPENDIX D
PROGRAM SCHEDULE

The program schedule for the completed High Energy X-ray Study is shown in figure D-1.

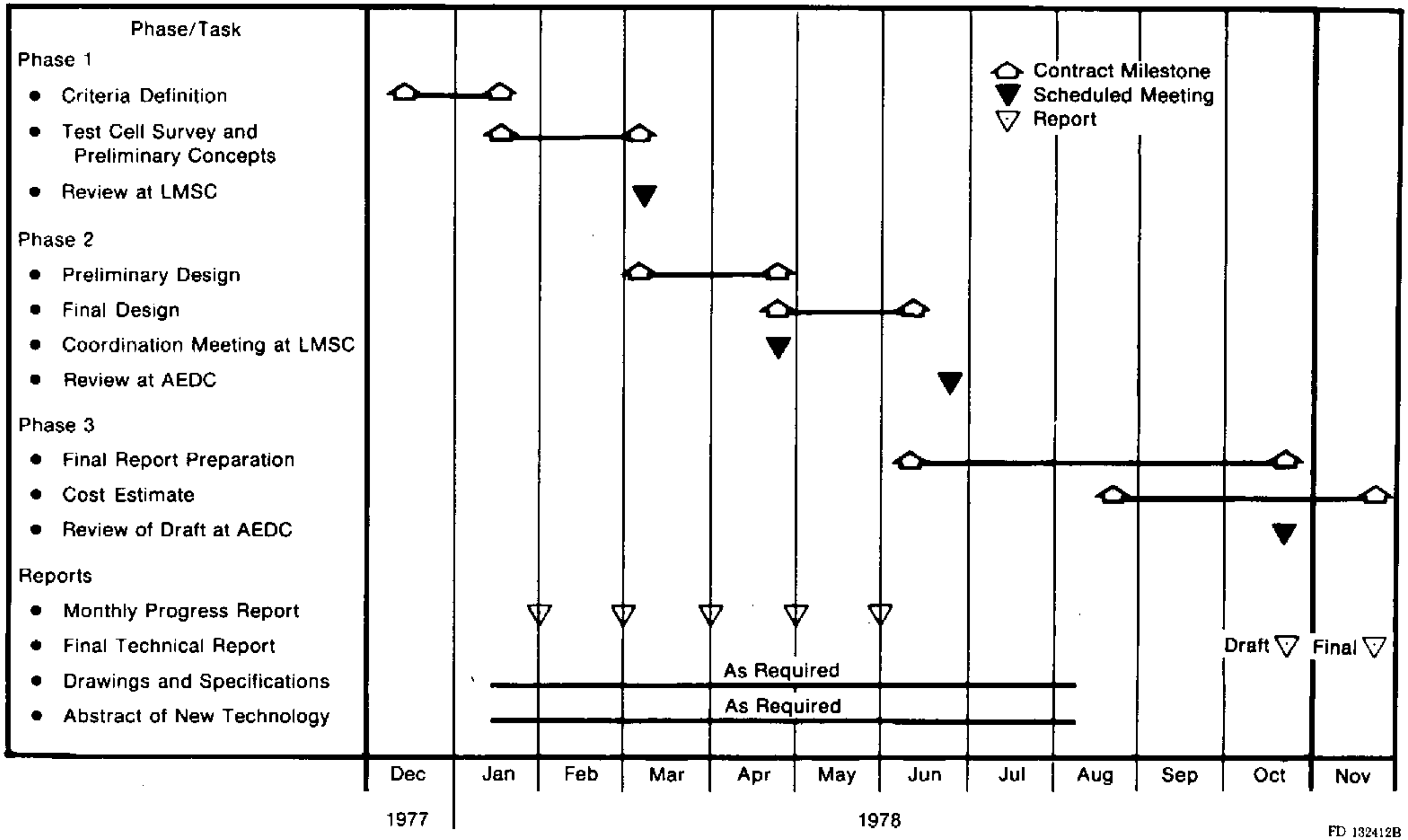


Figure D-1. High Energy X-ray Study Plan and Completed Schedule

DEFINITION OF TERMS
(X-RAY SOURCE)

Image Unsharpness (U_t)

The unsharpness is a measure of the blurring of the edges of an image on photographic film. The three sources of image blurring are film-screen, geometric, and scatter unsharpness. They are related by the equation

$$U_t = \sqrt[3]{U_f^3 + U_g^3 + U_s^3}$$

Since U_s is usually small in relation to U_f and U_g it is usually neglected.

Film-screen Unsharpness (U_f)

This is the component of image blurring due to scattering of X-ray photons in the photographic film and the image intensifying screen. It increases with increasing radiation energy and film grain size.

Geometric Unsharpness (U_g)

This is the spreading of the film image due to simple geometric considerations, and is given by

$$U_g = \frac{S}{D/T}$$

Source Spot Diameter (S)

This is the diameter of the area on the accelerator target from which the X-ray photons are emitted. It is determined by the diameter of the electron beam impinging on the target.

Source-to-Object Distance (D) or (SOD)

The distance from the X-ray source target to the part of the object being radiographed whose image is being measured.

Source-to-Film Distance (SFD)

The distance from the X-ray source to the film plane.

Object-to-Film Distance (T)

The distance from the source side of the object to the film plane.

X-ray Energy (V_o)

Radiographic accelerators are rated according to the maximum energy of the electrons in the electron beam that produces X-ray photons by impinging on a high Z metal target. The energies of the X-rays produced vary over a range with this rated energy as the upper limit. The energy determines the *quality* and the penetrating power of the beam.

X-ray Flux Intensity (I)

The X-ray itensity is a measure of the *quantity* of X-ray photons produced by a source. It determines the exposure time required to produce a given film image density.

Half-Value Layer (HVL)

This is the thickness of material that reduces the transmitted X-ray intensity by a factor of two. It is a function of the material and the X-ray energy.

DEFINITION OF TERMS
(PERSONNEL RADIATION SHIELDING)

Attenuation

The reduction of exposure rate upon passage of radiation through matter. This report is concerned with broad beam attenuation, e.g., that occurring when the field area is large at the barrier and the point of measurement is near the exit surface.

Concrete Equivalence

The thickness of concrete of density 2.35g cm^{-3} (147 lb ft^{-3}) affording the same attenuation, under specified conditions, as the material in question.

Controlled Area

A defined area in which the exposure of persons to radiation is under the supervision of a Radiation Protection Supervisor. (This implies that a controlled area is one that requires control of access, occupancy and working conditions for radiation protection purposes.)

Exposure

A measure of X or Gamma radiation based upon the ionization produced in air by X or Gamma rays. The special unit of exposure is the roentgen. *(For radiation protection purposes of this report, the number of roentgens may be considered to be numerically equivalent to the number of rads or rems.)*

High Radiation Area

Any area, accessible to individuals, in which there exists radiation at such levels that a major portion of the body could receive in any one hour a dose in excess of 100 millirems.

Interlock

A device which automatically causes a reduction of the exposure rate upon entry by personnel into a high radiation area. Alternatively, an interlock may prevent entry into a high radiation area.

Million Electron Volts (MeV)

Energy equal to that acquired by a particle with one electronic charge in being accelerated through a potential difference of one million volts (one MeV).

Personnel Monitoring Equipment

Any devices (e.g. film badges, pocket dosimeters, and thermoluminescent dosimeters) designed to be worn or carried by an individual for the purpose of estimating the dose received by the individual.

Primary Beam

Radiation which passes through the window, aperture, cone or other collimating device of the source housing.

Protective Barrier

A barrier of radiation attenuating material(s) used to reduce radiation exposure.

Primary Protective Barrier: Barrier sufficient to attenuate the useful beam to the required degree.

Secondary Protective Barrier: Barrier sufficient to attenuate the stray radiation to the required degree.

Rad

A special unit of absorbed dose equal to 10^{-2} J kg^{-1} (100 ergs g^{-1}).

Radiation Area

Any area, accessible to individuals, in which there exists radiation at such levels that a major portion of the body could receive in any one hour a dose in excess of 5 millirems, or in any 5 consecutive days a dose in excess of 100 millirems.

Leakage Radiation

All radiation coming from within the source or tube housing except the useful beam. (Note: Leakage radiation includes the portion of the direct radiation not absorbed by the protective source or tube housing as well as the scattered radiation produced within the housing.)

Scattered Radiation

Radiation that, during passage through matter, has been deviated in direction. (It may have been modified also by a decrease in energy.)

Radiation Safety Officer

The person directly responsible for radiation protection.

Rem

The unit of dose equivalent. For radiation protection purposes of this report which covers only X and Gamma radiation, the number of rems may be considered equivalent to the number of rads of absorbed dose in tissue or to the number of roentgens of exposure.

Roentgen (R)

A special unit of exposure equal to 2.58×10^{-4} coulomb per kilogram of air.

Uncontrolled Area

Any area access to which is not controlled by the licensee or registrant for purposes of protection of individuals from exposure to radiation and radioactive material, and any area used for residential quarters.

Use Factor (U)

Fraction of the time during which the radiation under consideration is directed at a particular barrier.

Workload (W)

The degree of use of an X-ray or Gamma-ray source. For Gamma-ray beam therapy sources, and for X-ray equipment operating at 4 MV or above, the workload is usually stated in terms of the weekly exposure of the useful beam at one meter from the source and is expressed in roentgens.

Exposure Rate

The exposure per unit time.

Installation

Radiation sources with associated equipment, and the space in which located.

Lead Equivalence

The thickness of lead affording the same attenuation under specified conditions, as the material in question.

Maximum Permissible Dose Equivalent (MPD)

For radiation protection purposes maximum dose equivalents that persons shall be allowed to receive in a stated period of time.

Milliroentgen (MR)

One-thousandth of a roentgen.

Occupancy Factor (T)

The factor by which the workload should be multiplied to correct for the degree of occupancy of the area in question while the source is "ON".

Radiation (Ionizing)

Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, by interaction with matter. In this report "radiation" refers to X-rays.

Radiation Protection Survey

An evaluation of the radiation safety in and around an installation.

RHM

Roentgens per hour at one meter from the effective center of the source (target).

Source

A discrete amount of radioactive material or the target (focal spot) of the X-ray accelerator.

LIST OF SYMBOLS, ACRONYMS, AND ABBREVIATIONS

AEDC	Arnold Engineering Development Center
D	Diameter
DE	Dose Equivalent
FOD	Foreign Object Damage
I/O	Input/output as in ports of a computer
LMSC	Lockheed Missile and Space Corporation
M	Magnification
MTF	Modulation Transfer Function
OFD	Object to Film Distance
PROM	Programmable Read-only Memory
P&WA	Pratt & Whitney Aircraft Group
RAM	Random Access Memory
RF	Radio Frequency
ROM	Read-only Memory
SFD	Source to Film Distance
SOD	Source to Object Distance
TELS	Turbine Engines Load Simulator
TOD	Target to Object Distance
TTY	Teletypewriter
TVL	Tenth Value Layer
μ_f	Detector Unsharpness

μ_g	Geometric Unsharpness
μ_s	Screen Unsharpness
μ_T	Total Unsharpness
W_x	Clearance Width in Plane of the Detector
2-D	Two-dimensional
3-D	Three-dimensional